PB86-194453

Further Case Studies on the Impact of Mesoscale Convective Systems on Regional Ozone and Haze Distributions

MESOMET, Inc., Chicago, IL

Prepared for

Environmental Protection Agency
Research Triangle Park, NC

Apr 86

U.S. Department of Commerce
National Technical Information Service
NTIS

PB86-194453

EPA/600/3-86/028
April 1986

FURTHER CASE STUDIES ON THE IMPACT OF MESOSCALE CONVECTIVE SYSTEMS ON REGIONAL OZONE AND HAZE DISTRIBUTIONS

by

Walter A. Lyons and Rebecca H. Calby

MESOMET, Inc.
35 East Wacker Drive
Chicago, IL 60601

EPA 68-02-4051

Project Officer

Francis S. Binkowski
Atmospheric Science Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

ATMOSPHERIC SCIENCE RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA/600/3-86/028	2.
3. RECIPIENT'S ACCESSION NO.	
4. TITLE AND SUBTITLE FURTHER CASE STUDIES ON THE IMPACT OF THE MESOSCALE CONVECTIVE SYSTEMS ON REGIONAL OZONE AND HAZE DISTRIBUTIONS	5. REPORT DATE April 1986 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Walter A. Lyons and Rebecca H. Calby	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS MESOMET, Inc. 35 EAst Wacker Drive Chicago, IL 60601	10. PROGRAM ELEMENT NO. CDWA1A/02-3193 (FY-86) 11. CONTRACT/GRANT NO. 68-02-4051
12. SPONSORING AGENCY NAME AND ADDRESS Atmospheric Sciences Research Laboratory - RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE EPA/600/09
15. SUPPLEMENTARY NOTES	

16. ABSTRACT

This report is a continuation of an earlier effort to study the impact of mesoscale convective precipitation systems upon distributions of aerosol and photochemical oxidant pollutants in the planetary boundary layer (PBL). Analyses of surface visibility and ozone data revealed a dramatic response in the boundary layer pollutant patterns to the passage of two very large convective storm systems. Regional visibilities, at times less than 5 km, increased dramatically over a multistate area to as high as 80 km. The resultant clean air region was termed a convective aerosol removal event (CARE).

In this study, a well defined CARE was found off the Georgia coast on 14 August 1980. Extensive mesoanalyses revealed that the clear air pocket embedded within a large surrounding PEPE (Persistent Elevated Pollution Episode) originated from a mesohigh system formed by a cluster of thunderstorms over northern Florida and Georgia the previous day. While the increase in regional visibility and the volumetric depletion of sulfate aerosol was of the same magnitude as in the MCC squall line case, the total mass of displaced aerosol was fully 50 times less.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 70
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

NOTICE

The information in this document has been funded by the United States Environmental Protecton Agency under Contract No. 68-02-4051 to MESOMET, Inc. It has been subject to the Agency's peer and administrative review and it has been approved for publication as an EPA document.

ABSTRACT

This paper represents a continuation of an earlier project to study the impact of mesoscale convective precipitation systems upon distributions of aerosol and photochemical oxidant pollutants in the planetary boundary layer (PBL). In the original study, using data collected during PEPE/NEROS-80, analyses of surface visibility and ozone data revealed a dramatic response in the boundary layer pollutant patterns to the passage of two very large convective storm systems; a mesoscale convective complex and an intense squall line. Regional visibilities, at times less than 5 km, increased dramatically over a multistate area to as nigh as 80 km. A technique was developed to estimate the total amount of aerosol, resumed to be primarily sulfate, that was displaced from the PBL. On the order of 38×10^6 kg of sulfate was apparently redistributed by the convective system. The resultant clean air region was termed a convective aerosol removal event (CARE).

In this study, a search of the existing PEPE/NEROS-80 data base was initiated to discover additional CAREs. A well defined CARE was found in GOES satellite imagery off the Georgia coast on 14 August 1980. Extensive mesoanalyses revealed that the clear air pocket embedded within a large surrounding PEPE (Persistent Elevated Pollution Episode) originated from a mesohigh system formed by a cluster of thunderstorms over northern Florida and Georgia the previous day. While the increase in regional visibility and the volumetric depletion of sulfate aerosol was of the same magnitude as in the MCC squall line case, the total mass of displaced aerosol was 7.7×10^5 kg, fully 50 times less. The responsible air mass thundershowers, far smaller than the systems first studied, clearly can result in less widespread but still significant impacts on PBL pollution.

In addition, the phenomenon of the pseudo-CARE was discovered. "Clear spots" embedded within large quasi-homogeneous PEPEs were found not to be associated with specific thunderstorms. In one case, large scale subsidence over the Great Lakes associated with lake breezes is hypothesized to have induced CARE-like clear zones which drifted as far south as the Ohio River. These observations have important implications for mesoscale deposition modeling and the interpretation of field program aerosol measurements.

ACKNOWLEDGEMENTS

Manuscript preparation and graphics support were provided by Lynn Newman, Jill Bauer, David Lau, Liv Nordem Lyons, and especially, Barbara Bishel. Their contributions are gratefully recognized.

Satellite imagery and supporting data for several case studies were kindly provided by Midwest Communications, Inc., Minneapolis, Minnesota.

Guidance and encouragement provided by the Project Officer, Dr. Francis Binkowski, ASRL, has been greatly appreciated.

CONTENTS

Abstract iii
Acknowledgements iv

1. Introduction 1
2. Conclusions 3
3. Recommendations 5
4. Background 7
5. Case Study: 13-14 August 1980 17
6. Case Study: 29-30 June 1975 39
7. Other CAREs and Pseudo-CAREs 52

Extended Bibliography 56

SECTION 1

INTRODUCTION

In the early 1970's meteorological satellites began providing graphic images of the long-range transport of aerosol pollutants. High resolution Landsat imagery tracked discrete plumes from power plants and steel mills for over 200 km (Lyons and Pease, 1973). Mohr (1971) speculated that large hazy areas seen over Europe from polar orbiting satellites were in fact synoptic scale air pollution events. By 1976, Lyons and Husar (1976), using the visible sensors of geostationary satellite systems, were able to provide circumstantial evidence that large areas of haze over the eastern United States were linked to synoptic scale episodes of sulfate pollution. This phenomenon, eventually termed a Persistent Elevated Pollution Episode (PEPE), has since been extensively studied (Vaughan et al., 1982). Given the frequent reoccurrence of highly polluted boundary layers extending over multi-state areas, questions soon arose as to the fate of these pollutants. Transport through the atmosphere results not only from horizontal advection, but from vertical motions due to mesoscale convective processes. Initial attention was paid to non-precipitating cumulus congestus clouds (Ching, 1982). Speculation as to the impact of deep three-dimensional cumulonimbus-scale vertical convective motions soon arose (Scott, 1978; Cotton, 1983). Lyons et al. (1978) hypothesized that the impact of large thunderstorm systems should be clearly visible in the hazy air masses when viewed by geostationary satellite systems. As part of the PEPE/NEROS-80, an active effort was launched to use the GOES satellites to detect mesoscale convective system (MCS) thunderstorm impact upon boundary layer aerosol patterns.

Lyons and Calby (1983) presented an extensive case study which indicated massive displacement of sulfate aerosol and ozone from the boundary layer over a multi-state area of the mid-Atlantic states due to the passage of a mesoscale convective complex (Maddox, 1980) and a related squall line system. A large clear area, subsequently termed a Convective Aerosol Removal Event (CARE) was detected both in the GOES visible satellite imagery and by the analysis of surface visibility reports. In Lyons, Calby, and Keen (1985) it is hypothesized that thunderstorms are an important sink for sulfate aerosols and other pollutants, not only due to wet removal to the surface, but more importantly, by the injection of massive amounts of pollutants into the middle and upper troposphere

as a result of thunderstorm convective updrafts. Strong downdrafts replace the near-surface air with air from mid-tropospheric levels. The perturbations induced in the antecedent polluted boundary layer may last for one or more days until horizontal mixing processes diffuse the CARE out of existence.

These preliminary results raised a number of intriguing questions. First, are CAREs formed by smaller storms, i.e., the more typical air mass thundershowers which dominate the southern and eastern United States during the warm season? Were the events of 2 August 1980 a unique occurrence, not likely to be repeated with enough frequency to invalidate current transport and deposition modeling efforts (NCAR, 1984)? Also, are all such turbidity inhomogeneities detected in GOES satellite imagery the result of thunderstorms or are there other mechanisms which could come into play? These questions will be addressed in the following report.

SECTION 2

CONCLUSIONS

The primary purpose of this project was to determine if a convective aerosol removal event (CARE) could be associated with small air mass thunderstorm systems. This is in contrast to the extremely large CARE generated by a massive mesoscale convective complex and squall line on 2 August 1980 (Lyons and Calby, 1983). On 13 August 1980, a cluster of small local thunderstorms developed over northern Florida and southern Georgia. Detailed mesoanalyses showed that several smaller mesohighs eventually congealed into one larger system which ultimately covered an area of 172,000 km^2. By the next morning an area of improved visibility moved across eastern Georgia and extreme southern South Carolina. Visibility at the affected stations improved to an average of 18 km, for a total increase of 7.6 km. The estimated mean volumetric decrease of sulfate aerosol concentration within this CARE was on the order of 15 ug/m^3. These changes were of the same order as those associated with the MCC and squall line of 2 August, indicating little significant difference in the basic efficiency of the process. However, the total mass of sulfate estimated to have been displaced from the CARE was only 7.7×10^5 kg, or approximately 1/50 of that in the first case study. Thus, evidence is presented that smaller thunderstorm clusters can produce CAREs of similar intensity, but in smaller geographical areas and, consequently, with lower sulfate mass (and presumably oxidant) displacement from the polluted boundary layer.

Since, with some exceptions, the updrafts of convective precipitation systems originate in and draw much of their mass flux from the polluted planetary boundary layer, this leads to speculation as to the ultimate fate of the displaced aerosol. A simple schematic model is presented. Some of the aerosol is, of course, removed to the surface by wash-out and wet deposition mechanisms. The radially outward spreading mesohigh, acting as a plow, undercuts the polluted boundary layer air, physically uplifting some of the material in homogeneous layers to altitudes perhaps as high as 3000 m AGL. Given the intense vertical transport within a storm's convective tower, large quantities of boundary layer pollutants are transported to great heights. Some of the material is detrained from the cumulonimbus tower into the middle troposphere. It is suspected that most of the material is eventually evaporated from the anvil cloud debris near the base of the tropopause. Some material may be actually injected into the stratosphere by overshooting turrets associated with the more intense thunderstorms. As pointed out by Cotton (1983), cumulonimbi are noted for their rain producing capability. Certainly some of the pollutants become involved in the water phase chemistry and contribute to acidic precipitation. What remains to be quantitatively evaluated is the percentage of the original boundary layer pollutants that are vented into the anvil region of the cloud

versus what are rained out to the surface. Since the more intense supercell thunderstorms are known to have comparatively low precipitation efficiencies, these are postulated to be perhaps the most efficient venters. The probable role that thunderstorms play as sinks of boundary layer pollution, not to the surface, but to the upper troposphere, may need to be seriously considered as components of regional deposition models.

One totally unexpected result of the project was the discovery of the pseudo-CARE. Areas of lower turbidity or "holes" within the hazy PEPE air mass, originally thought to be thunderstorm induced CAREs, were unable to be related to specific mesoscale precipitation systems. During a two day period in June, 1975 there was intense subsidence over the Great Lakes associated with lake breezes. These in turn deformed the polluted boundary layer, and appear to have significantly depressed the top of the aerosol layer. Upon cessation of the lake breeze these "aerosol holes" drifted with the northeasterly flow into the Ohio Valley, maintaining themselves for 18 to 24 hours. Other apparent pseudo-CAREs were discovered, including one long, narrow swath of reduced cumulus convection and apparent increased turbidity that was associated with a synoptic scale mid-tropospheric subsidence event.

SECTION 3

RECOMMENDATIONS

With completion of two case studies, we have now found evidence that three major classes of thunderstorms generate convective aerosol removal events (CAREs). The mesoscale convective systems studied were: an air mass thunderstorm cluster, a mesoscale convective complex, and a squall line. At least one major type of thunderstorm has not yet been studied, i.e., the isolated supercell thunderstorm. In any case, additional studies for all types of thunderstorms are required to better understand the relationship between the storm type, total rainfall, and sulfate displacement from the polluted boundary layer.

While the use of surface meteorological data allows reasonable estimates to be made of the total aerosol displaced during a CARE, these data, in turn, provide virtually no information as to the ultimate fate of these aerosols. A key question is what is the partitioning between wet deposition versus injection into the free troposphere? As highlighted by Cotton (1983), these field observations are necessary to support the various hypotheses of numerical cloud venting modelers. An intensive field program is needed during which several different approaches could be employed. First, the mass budget for sulfate and other aerosols during the life cycle study of an isolated intense thunderstorm shall be determined. This study should attempt to determine the partitioning of aerosol mass to the surface. It should also determine how much remains at midlevels and at the base of the tropopause, once injected into the free troposphere, and ideally, if any is injected into the stratosphere. Other tracers besides sulfates can be employed. Ozone, since it is less soluble than many gases and does not participate directly in the precipitation process, should be measured. However, it should be noted that extensive intrusions of stratospheric ozone into a tall cumulonimbus cloud circulation could complicate the interpretation of the results. Tracers such as the new generation of hydrocarbons could prove highly useful. By "spiking" the updraft around an isolated and identifiable thunderstorm and measuring its total final redistribution, insight would be gained into the vertical transport and dispersion properties of a thunderstorm. The upcoming National STORM Program (UCAR, 1983) provides an ideal setting for such an experiment.

Additional efforts should be made towards the collocation of meteorological wet and dry deposition and air quality monitoring sites for both routine and special networks. It is extremely difficult to interpret the results of changes in aerosol and other pollutant concentrations if corresponding onsite meteorological information is not available. Furthermore, whenever possible, measurements, particularly of sulfate, should be made on shorter than 24 hour

intervals. Mesoscale systems are inherently short period phenomena. Long sampling periods eliminate the high frequency fluctuations which are critical to the understanding of the mechanisms and impacts of thunderstorm aerosol displacement. Interpretation of aerosol patterns as seen in satellite imagery provides a valuable overview of atmospheric processes. However, they are very difficult to interpret, as are on-site measurements of aerosols and other pollutants without the appropriate supporting meteorological information. It must be understood that the data collection and archival systems of the nation's meteorological services are extremely crude and do not provide (at least cost-effectively) most of the information required for the proper analysis of satellite and pollutant measurements. High resolution radar data, real-time lightning stroke data, and high resolution animated GOES imagery are in general not archived in convenient formats as part of routine government operations. This must be done on a real-time basis by using currently available operational facilities available from both the government and private sectors. The attempts to acquire such data after-the-fact are costly and will almost always produce lower quality and less useful information to support field program data analyses.

The unexpected discovery of the pseudo-CARE phenomenon suggests that the air quality community should further interface with dynamic meteorologists. There appear to be a number of dry atmospheric processes which lead to mesoscale subsidence phenomena which significantly alter boundary layer pollution profiles. The intrusion of large amounts of mid-tropospheric air into the boundary layer, unless recognized as such, could seriously bias the interpretation of measurements made during aerosol transport and transformation experiments.

SECTION 4

BACKGROUND

Synoptic scale pollution episodes occur with considerable frequency over the eastern United States during the summertime (Watson and Saucier, 1979). There are strong correlations between reduced regional visibility, particulate sulfate mass, and photochemical oxidants during such PEPE events (Altshuller, 1985). Since most sulfate aerosol mass is submicron in size, they are excellent scatters of light (White et at., 1976) and are therefore easily visible to the VISSR scanning system of the GOES geostationary satellite (0.5 - 0.9 micrometer wavelength). Figure 1 shows a typical GOES medium resolution image over the eastern United States during an all too rare summertime period in which the region is dominated by a comparatively "clean" polar anticyclone. Note the sharp contrast between land and water and the visibility of smaller topographic features. By contrast, Figure 2, taken during a massive PEPE episode in August, 1976, reveals extensive areas of haziness over large portions of the eastern United States and southeastern Canada. A sharp discontinuity in the turbidity also plainly delineates a cold frontal boundary, which is, of course, the demarcation separating air masses of different temperature, moisture, and aerosol concentrations. Aerosols in fact make an excellent natural atmospheric tracer. This fact was pointed out by Lyons and Pease (1973) from point source plumes, by forest fire smoke (Chorowski et at., 1981), and even dust storms (Norton et al., 1980). Lyons and Olson, (1973) used smoke photography to infer important details concerning the nature of 3-dimensional lake breeze circulations around the Chicago metropolitan area. Photography and airborne aerosol measurements were used to track the Chicago urban plume for long distances downwind (Lyons and Ruben, 1976).

A PEPE represents an accumulation of secondary aerosol mass distributed over a wide area for an extended period of time (up to three weeks). Eventually all material is removed from the atmosphere by a variety of processes. It is generally assumed that the aerosols are returned to the earth's surface via dry or wet deposition. The manner by which aerosols are removed and returned to the earth during precipitation has undergone extensive analysis. Among the earlier of the larger field programs, the OSCAR experiment (Easter, 1984), the emphasis was primarily upon removal mechanisms within stratiform clouds. The same is true of the study of mesoscale variability of urban wet deposition patterns reported by Patrinos (1985), and in the recently conducted study by Battelle Pacific Northwest Laboratories (Hadlock, Personal Comm.). Numerous theoretical studies such as Hegg et al. (1984) and Daum et al. (1983) also have concentrated on stratiform warm frontal clouds. But as Scott (1978), Hales and Dana (1979), and Lyons and Calby (1983) have pointed out, stratiform precipitation mechanisms are profoundly different from those associated with convective storms. There are orders of magnitude of difference in the vertical motion involved. This

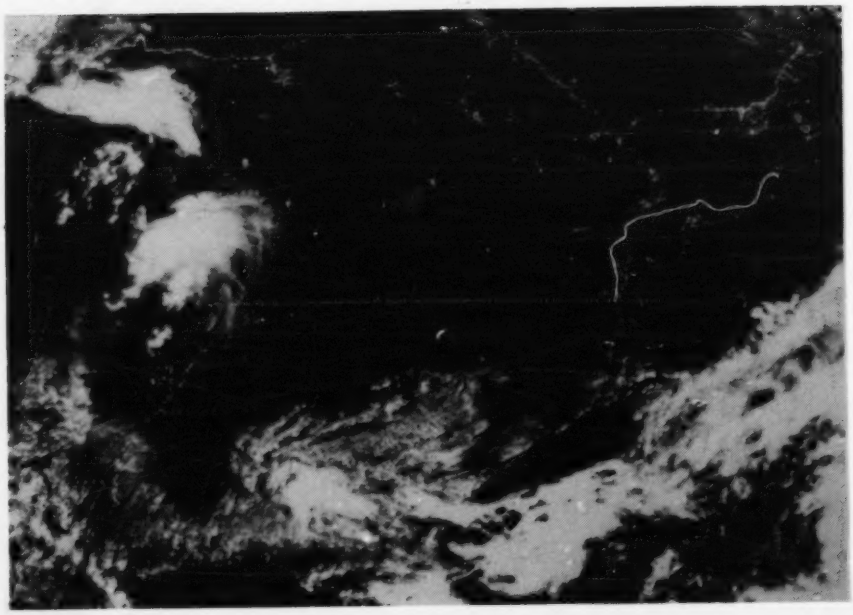

Figure 1. GOES satellite 2 km resolution visible image, DB5 sector over eastern United States during a period of an exceptionally clean summertime air mass. Notice the sharp resolution of ground features and the strong land/water contrasts.

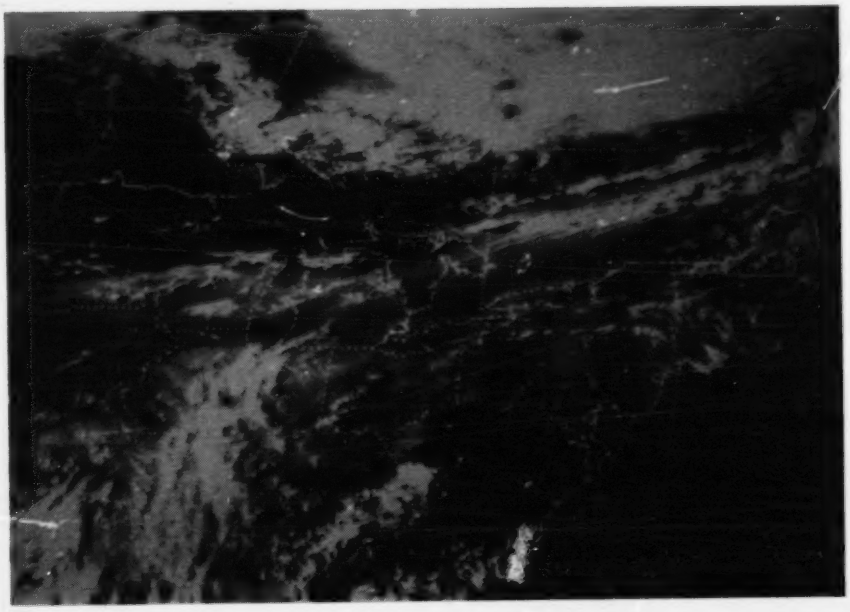

Figure 2. GOES satellite 2 km resolution visible image, during the major PEPE episode of August, 1976. Note the milky haze and the reduced ground contrast over much of the eastern United States. Also evident is a sharp discontinuity of turbidity associated with a cold front stretching from southern Minnesota to central Quebec.

realization has prompted studies of vertical ozone transport within cumulus congestus clouds by Greenhut et al. (1984). Convective clouds range through their own enormous spectrum of sizes and mass fluxes from the smallest fair weather cumulus humilis through the typical air mass thundershower (Byers and Braham, 1949), to the cold frontal squall line (Hane, 1973), the mesoscale convective complex (Maddox, 1980), and the isolated, but intense supercell thunderstorm (Browning and Ludlam, 1962; Klemp and Wilhelmson, 1978). As noted by Auvine and Anderson (1972) and Mack and Wyle (1982), the mass flux from the boundary layer in an intense thunderstorm can easily approach 10^{14} g/sec. In response to this mass evacuation, there is replacement by lateral convergence, plus downdrafts from mid-tropospheric levels into the surface layers. This massive exchange of air has profound consequences when considering the fate of boundary layer pollutants.

The removal of aerosol mass from the polluted boundary layer and its replacement by large quantities of cleaner tropospheric air was graphically demonstrated by Lyons, Calby, and Keen (1985) in their study of the massive Mesoscale Convective Complex (MCC) which spread across the mid-Atlantic states on 1-2 August 1980. Interactive image enhancement techniques, using the McIDAS system for processing of GOES visible satellite data (Figure 3) showed an extensive CARE over Virginia and North Carolina, accompanied by a large area of elevated aerosol layers over portions of Georgia and South Carolina (Shipley et al., 1983). The CARE's impact was so extensive that it was plainly visible in routinely available GOES imagery more than 24 hours after the event had occurred (Figure 4).

As indicated above, there are many types of thunderstorms. Some are steady state while others are clearly cyclical in their processes. Some remain as essentially single cell entities while others are multi-cell clusters (Newton, 1966). Some convective storms lack energy even to reach the tropopause while others penetrate a substantial distance into the stratosphere. There is little doubt that precipitation efficiencies within such storms vary widely (Braham, 1952). It is clear that massive amounts of air, water vapor, and potentially, pollutants are evacuated from the boundary layer into the cloud tower and are eventually redistributed via several mechanisms including: (1) wash-out and wet removal processes, (2) transport as cohesive layers to higher altitudes by the plowing effect of undercutting downdrafts-induced gust fronts, (3) detrainment into the free troposphere, (4) accumulation near the tropopause upon evaporation of the cumulonimbus anvil cloud debris, and possibly (5) injection into the stratosphere through tropopause penetration by intense convective turrets atop the storm.

It is well known that the dynamics of even a relatively simple supercell cumulonimbus are extremely complex (Browning, 1964). Figure 5 shows, in schematic form the basic structure and air flow of a typical thunderstorm. While there are exceptions, most thunderstorm updrafts largely originate from the surface to approximately 2,000 m, which represents the depth of the polluted boundary layer. Hence, these pollutants become an integral part of the mass flux

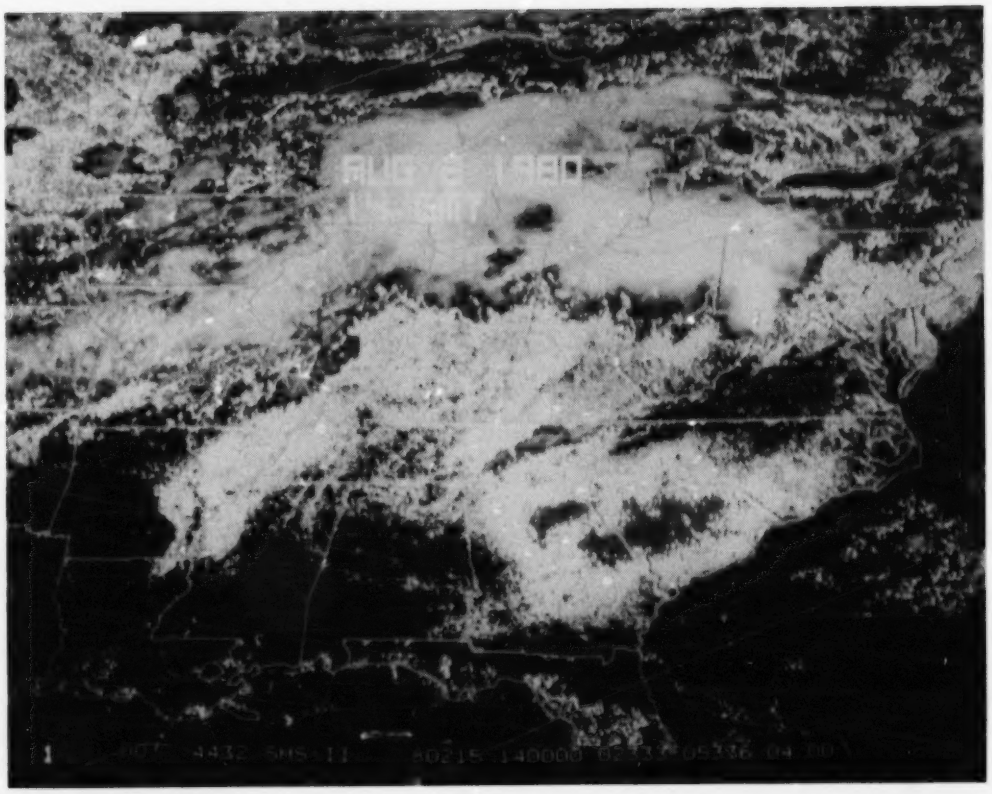

Figure 3. McIDAS generated enhanced visible image showing cloud and haze patterns over the eastern United States at 1400 GMT, 2 August 1980. Dense haze centered in Georgia and South Carolina is enhanced, as is the distinct low turbidity CARE over northern North Carolina, Virginia, and parts eastward (see Lyons, Calby, and Keen, 1985).

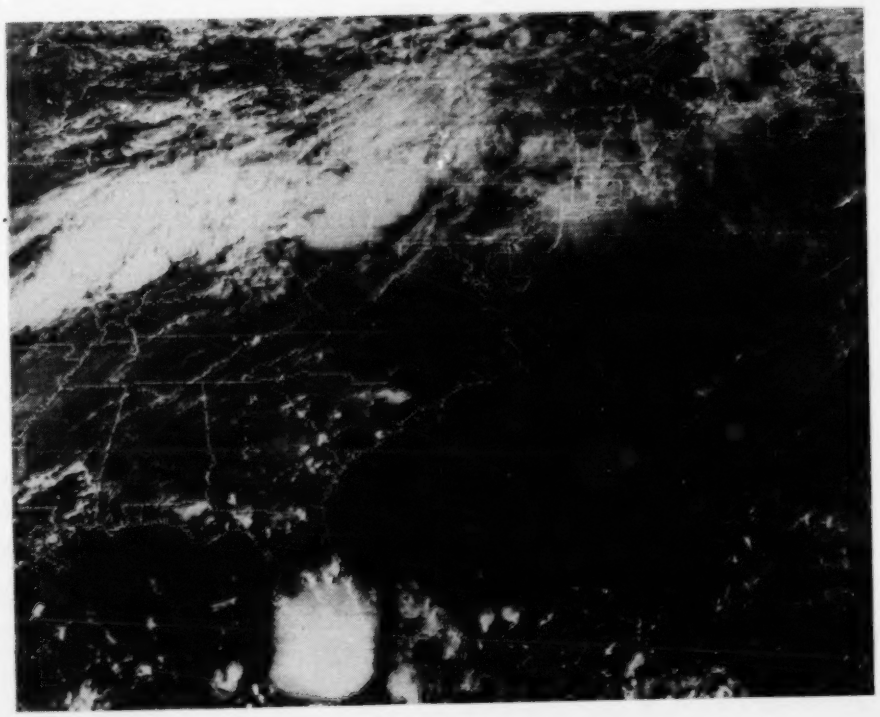

Figure 4. GOES 2 km resolution visible image, DB5 sector, 2230 GMT, 02 August 1980 showing a massive CARE stretching from North Carolina and Virginia eastwards to the Atlantic Ocean.

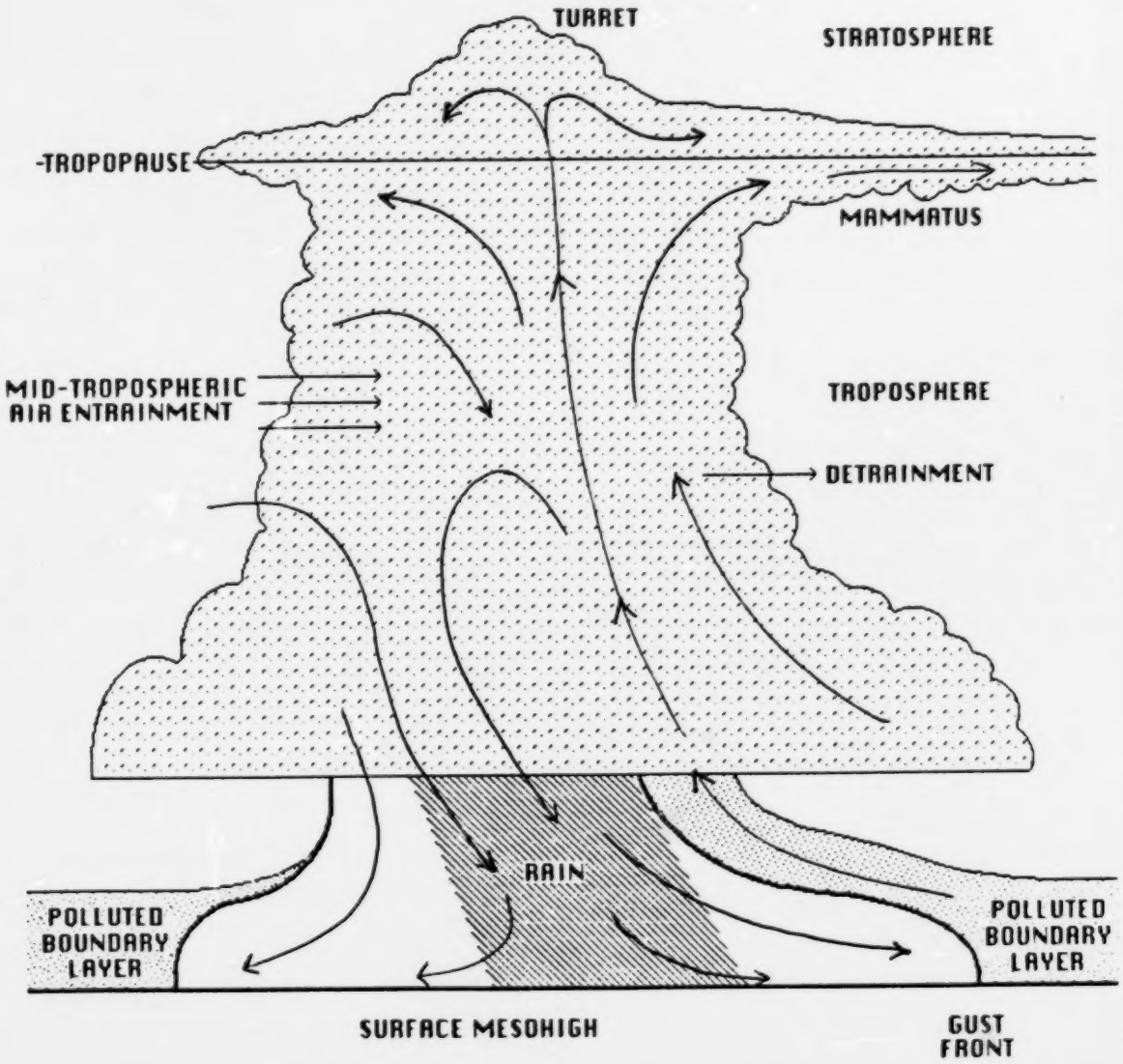

Figure 5. Schematic of the typical circulation within an intense isolated thunderstorm.

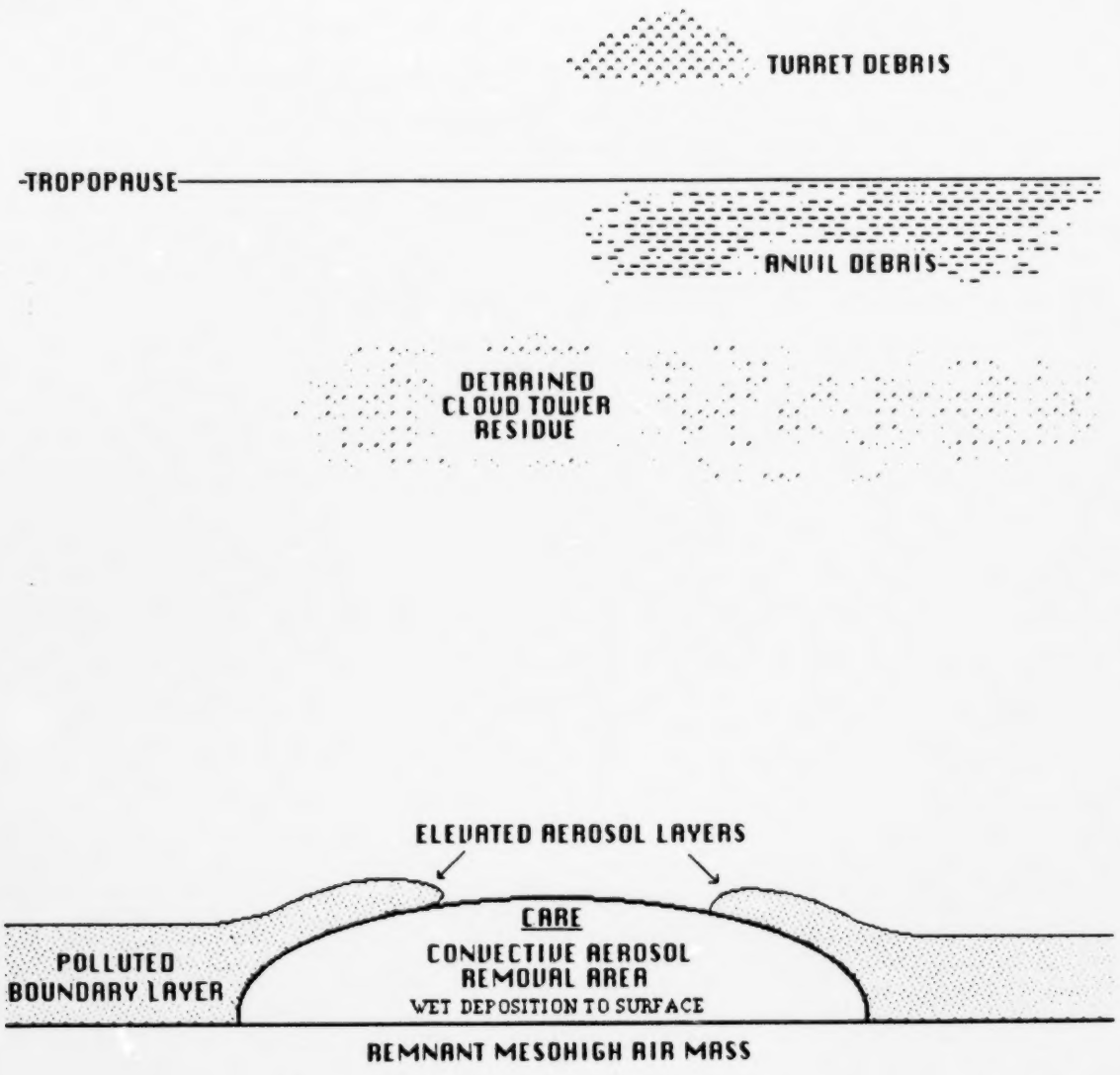

Figure 6. Resultant distribution of particulate matter from the originally undisturbed polluted planetary boundary layer as a result of the major convective storm event as postulated in Figure 5.

into the storm. It should also be noted that due to the convergent nature of the low-level cumulonimbus circulation, air is drawn from far beyond the physical boundaries of the thunderstorm itself to be processed by one of the mechanisms listed above.

Figure 6 suggests the resultant fate of the particulate matter from the originally undisturbed planetary boundary layer as the result of a major convective storm event. Polluted boundary layers can be undercut by the outflowing higher density air mass behind the thunderstorm gust front. This effect has been documented in some detail by Shipley et at. (1983), Browell et al. (1983), and Orndorff (1982). There is less direct evidence of the other processes upon which we have speculated. Frequent observation of what appears to be layers of brown aerosol matter at the base of the tropopause when flying in jet aircraft during the summer, lend additional credence to this speculation. Whether or not there physically can be an injection of material into the stratosphere by the penetrative turrets atop a vigorous cumulonimbus cloud is a matter of considerable speculation. If penetration occurs, it suggests the possibility of an increase in anthropogenic sulfate material in the lower stratosphere, which would begin accumulating over the course of time due to the extremely small settling velocities of the submicron particles, as well as the lack of precipitation scavenging mechanisms.

While large amounts of mass are injected upwards, a corresponding compensation mechanism occurs. Penetrative precipitation driven downdrafts produce a mesohigh pressure system (Fujita, 1959), which radially spreads outwards behind a gust front, acting as a plow and undercutting boundary layer air. It might be forced upwards by several hundred to several thousand meters (Goff, 1976). As Wakimoto (1982) pointed out, gust fronts from even small thunderstorms can extend more than 50 km from the rain area. These gust fronts are often marked by so-called "rope clouds" which have been frequently studied by satellite imagery (Purdom, 1973; Woods, 1983; Haase and Smith, 1984). Figure 7 presents a graphic, but by no means unusual, example of the phenomenon. A highly divergent mesohigh is spreading air of largely mid-tropospheric origins over a wide area. A dramatic rope cloud extends from east Texas through western portions of the state and northwards into New Mexico, originating from a large cluster of thunderstorms more than nine hours earlier in Oklahoma (Figure 8). If this event were to have occurred during a PEPE, a dramatic change in regional air quality would have occurred in an area two-thirds the size of our largest state. The larger fraction of the region affected would never have experienced cloudiness, much less rainfall.

This paper attempts to continue an on-going series documenting the CARE mechanism. In the following sections we will concentrate on much smaller isolated air mass thunderstorm clusters.

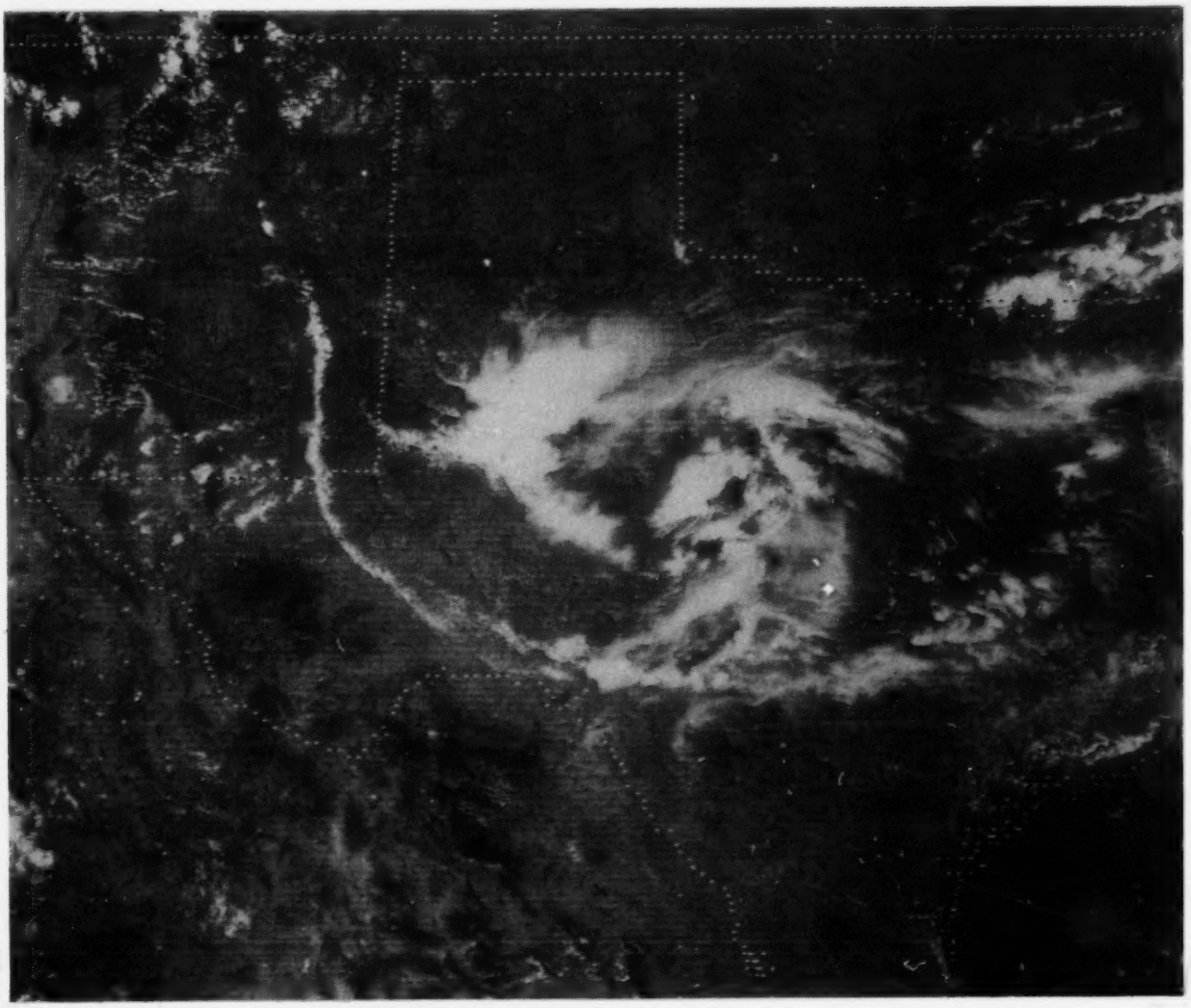

Figure 7. GOES visible imagery, 1 km resolution, KA2 sector, at 1730 GMT, 30 August 1984. Notice the extensive rope cloud extending from eastern New Mexico into east central Texas along with remnants of a dissipated thunderstorm complex over north central Texas.

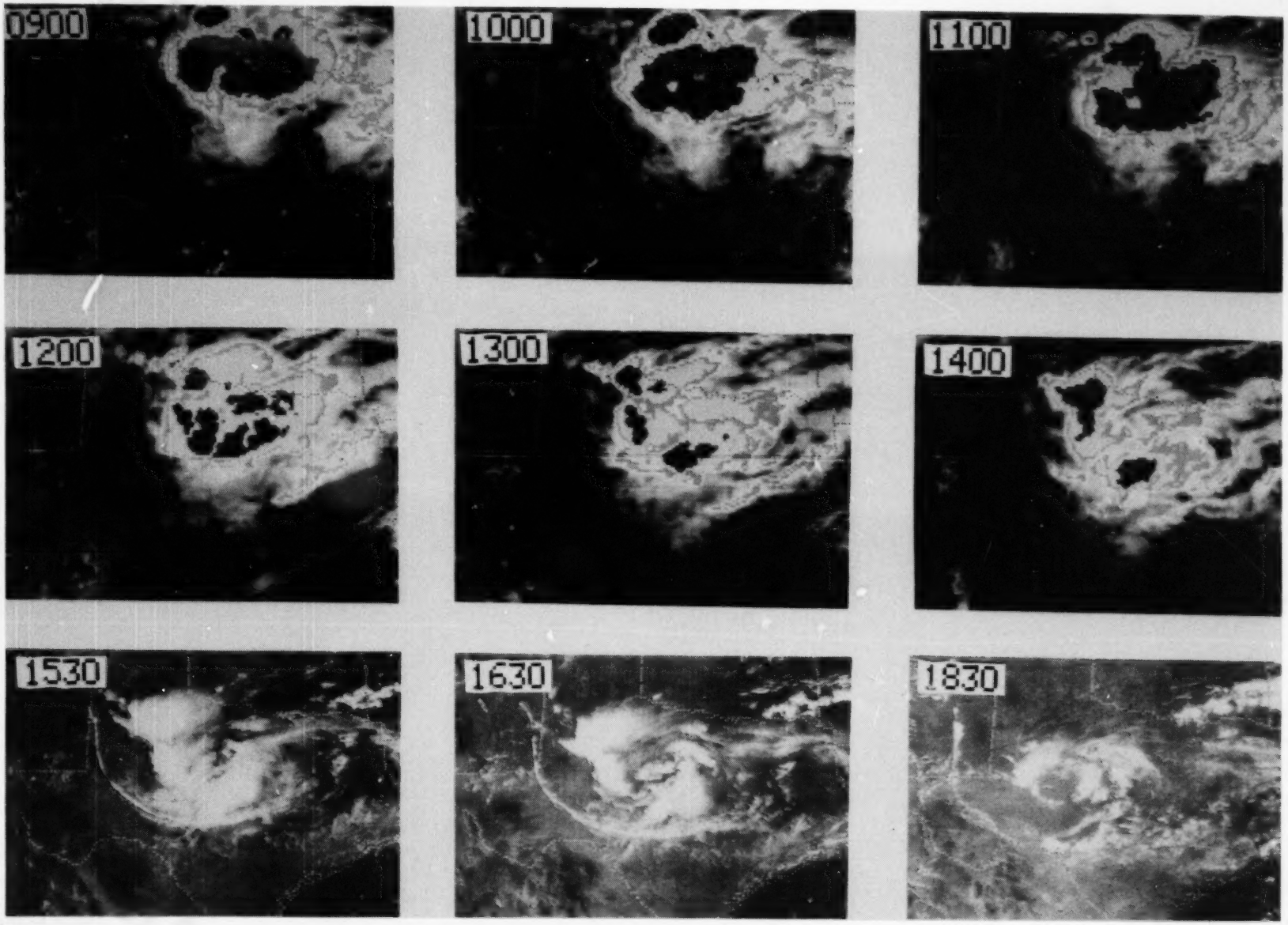

Figure 8. Mosaic of GOES infrared and visible satellite images, extending from 0900 GMT to 1830 GMT, 30 August 1984. Notice the southward progression of the main thunderstorm complex and the development of the rope cloud at the leading edge of the mesohigh gust front.

SECTION 5

CASE STUDY: 13-14 AUGUST 1980

The major component of this project was performing detailed mesoanalyses of a cluster of air mass thunderstorms and their resultant CARE over the southeastern U.S. on 13-14 August 1980. As a preamble to the analyses, a brief description of the synoptic regime and attendant pollutant patterns is presented. By 1200 GMT 13 August, a trailing cold front associated with a low pressure system which had moved across Nova Scotia, was positioned off the Atlantic coast and across Georgia as shown in Figure 9. This frontal zone moved northward during the day of the 13th and by 2100 GMT was better characterized as a stationary front along the South Carolina - North Carolina border. The front thereafter underwent frontolysis.

The clear air within the high pressure north of the front began to accumulate pollutants from local sources and, as aged PEPE air which was undercut by the shallow front, mixed back to the surface with daytime convection. Thus, pollutant levels, especially ozone, were increasing during the afternoon of 13 August from south Georgia northwards. This increasing pollutant loading can be monitored by the degradation of regional visibilities. In the absence of fog, high relative humidity, or precipitation, visibility can be used as a useful surrogate for sulfate aerosol measurements. These submicron anthropogenic aerosols scatter light highly efficiently (Altshuller, 1985). Visibility plots at 1800 GMT (Figure 9) show the clean (high visibility) air extending from the Ohio Valley into Virginia, but with distinct hazy regions dominating the Southeast.

A more detailed analysis of the regional visibility pattern is given in Figures 10a,b using properly screened data from 1800 GMT, 13 and 14 August 1980, respectively. Only those data that were not concurrent with obstructions to visibility (rain, fog) or dewpoint depressions of 3° F or less were included. During mid-day of 13 August, a broad band of low visibility air extended from Mississippi into the Carolinas, where it was particularly hazy. Visibilities of 3 mi (5 km) or less were noted. A slight thinning of the haze to 10 mi (16 km) in southern Georgia is believed to be the remnant of an earlier CARE. Only 24 hours later, a dramatic change in the pattern had occurred (Figure 10b). Over large areas of Georgia and South Carolina, and eastward into the Atlantic, visibilities had improved markedly, reaching 20 mi (32 km) at Savannah, GA. No synoptic front had traversed this region. Surface winds were essentially light and variable, with a slight westerly drift.

At Jacksonville, Florida, thunderstorms were reported from 1600-2000 GMT on 13 August 1980. Several cells crossed the Jacksonville area during that time. The end result was that between 1500-2300 GMT, visibilities improved from 7 mi (11 km) to 15 mi (24 km), the temperature dropped from 90° to 78° F, and dewpoint temperature dropped from 78° to 74° F. Atmospheric pressure was variable. Only 0.03" of rain was reported with these cells.

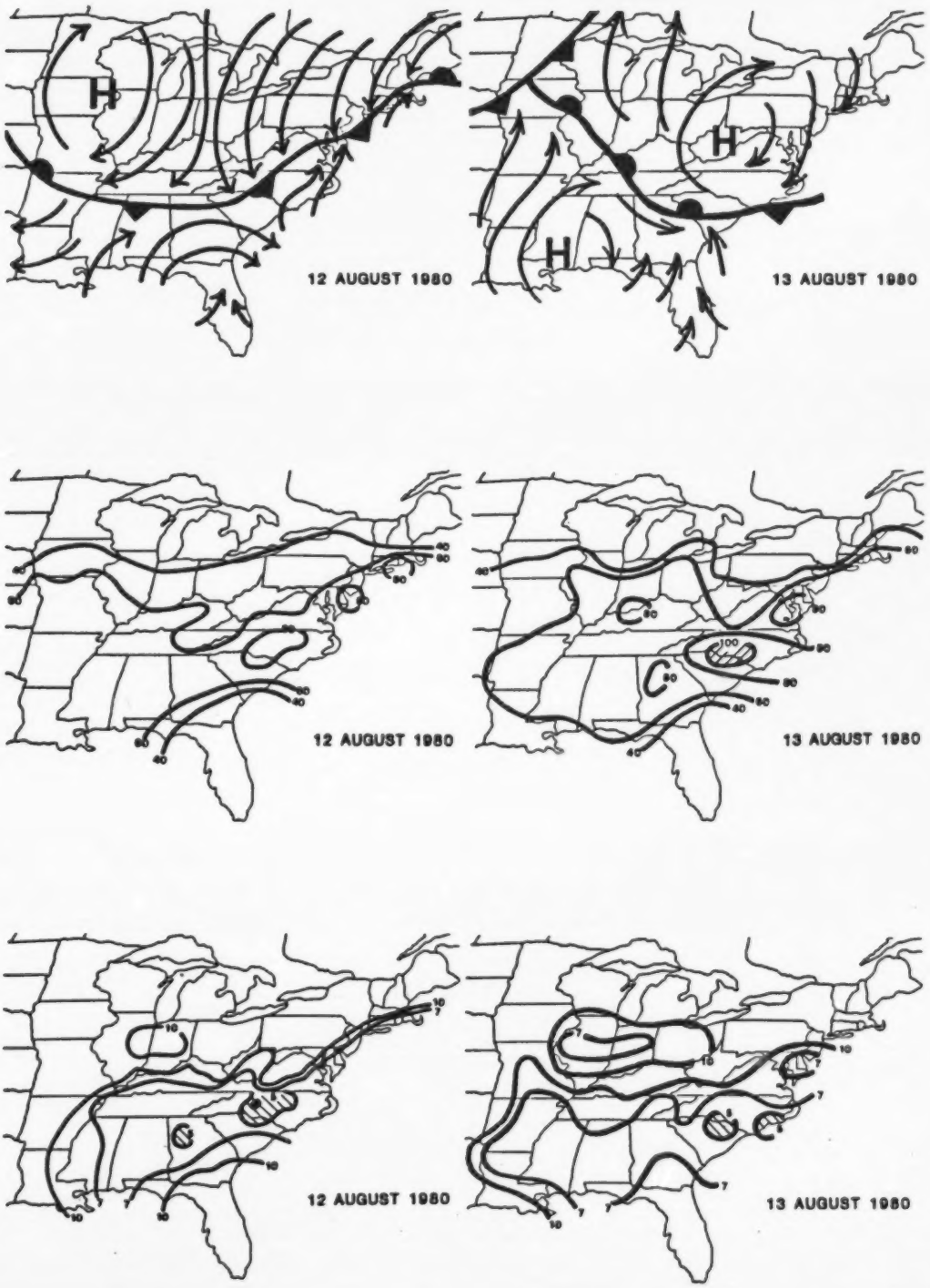

Figure 9. Synoptic scale surface winds, ozone, and visibility conditions observed on 12 and 13 August 1980 in the eastern United States. See Lyons and Calby (1982b).

Figure 10a. Regional visibility pattern, 1800 GMT, 13 August 1980 over the southeastern United States. Visibility as low as three miles is present from Georgia into North Carolina and eastwards over the Atlantic. To obtain these reports all surface weather reports were screened to remove those cases where rainfall or fog was reported as an obstruction to visibility or the temperature and dewpoints were closer than 3° F.

Figure 10b. Same as above, except for, 1800 GMT, 14 August 1980.

At Alma, Georgia, a thunderstorm began at 2122 GMT. As the gust front crossed Alma from the east southeast between 2100 and 2200 GMT, the temperature dropped from 97° to 82° F, and pressure rose almost 2 mb. Since Alma is not a 24 hour reporting station, it is difficult to estimate the changes in dewpoint and visibility because the observations ended as the rain was ending. At least 0.41" of rain were reported.

At Savannah (Figure 11), a thunderstorm was reported, beginning at 2126 GMT. Only a trace of rain resulted from the storm at the observing site. Between 2100 and 2200 GMT, the temperature dropped from 89° to 83° F, the dewpoint dropped from 76° to 72° F, and the pressure rose over 1 mb. Visibility increased from 7 mi (11 km) to 10 sm (16 km) by 2300 GMT. These storms were clearly visible in the GOES satellite image. They are small in comparison to an MCC, but are still fairly large for air mass thundershowers.

The thunderstorms dissipated by the time the weak gust front reached Beaufort, South Carolina, further to the east, around 2300 GMT. There was a wind shift, temperature, and dewpoint drop and a pressure rise was reported at 2300 GMT. The outward spreading and advection of the cold air dome apparently slowed as wind speeds became light and variable during the late evening/early morning hours.

At Charleston, South Carolina, on 13 and 14 August, no obvious gust front passages or thunderstorms were apparent. Temperatures did drop in response to the sea breeze front at 1800 GMT, 13 August, and afternoon cloudiness. Due to the moist air with dewpoint depressions of approximately 4° F, visibilities were degraded throughout the evening, and it is difficult to ascertain exactly when the cleaner air advected into the Charleston area. Perhaps the pool of cleaner air remained above the nocturnal radiation inversion and mixed to the surface as solar heating commenced on 14 August. Visibilities increased from 7 mi (11 km) to 15 mi (24 km) between 1100 GMT and 1300 GMT, 14 August 1980.

In order to better interpret these single station reports, we examined radar and surface precipitation data for indications of the suspected CARE. Figure 12 is a mosaic comprised of hourly digitized weather radar reports which are transmitted over the NAFAX facsimile circuit. It is apparent that typical summertime "air mass" convective storms developed over much of the southeast. These storms were locally intensified by the vigorous sea breeze circulations of the Gulf and Atlantic coasts. It should be kept in mind that the NAFAX charts are prepared from MDR (manually digitized radar) gridded data which greatly exaggerate the areal coverage of the precipitation echoes. Regardless, there were vigorous local storm systems throughout the region. As indicated by radar, echo tops reached 60,000 ft. in northern Florida and southern Georgia. Rainfall reports are summarized in Figure 13. Pockets of intense local rainfall were found. These were of the size and intensity to indicate the probable presence of organized mesoscale high pressure systems (Fujita, 1959; Purdom, 1973, 1976). These mesohighs would be comprised largely of air convected downward, possibly from mid-tropospheric levels, in the evaporatively driven downdrafts.

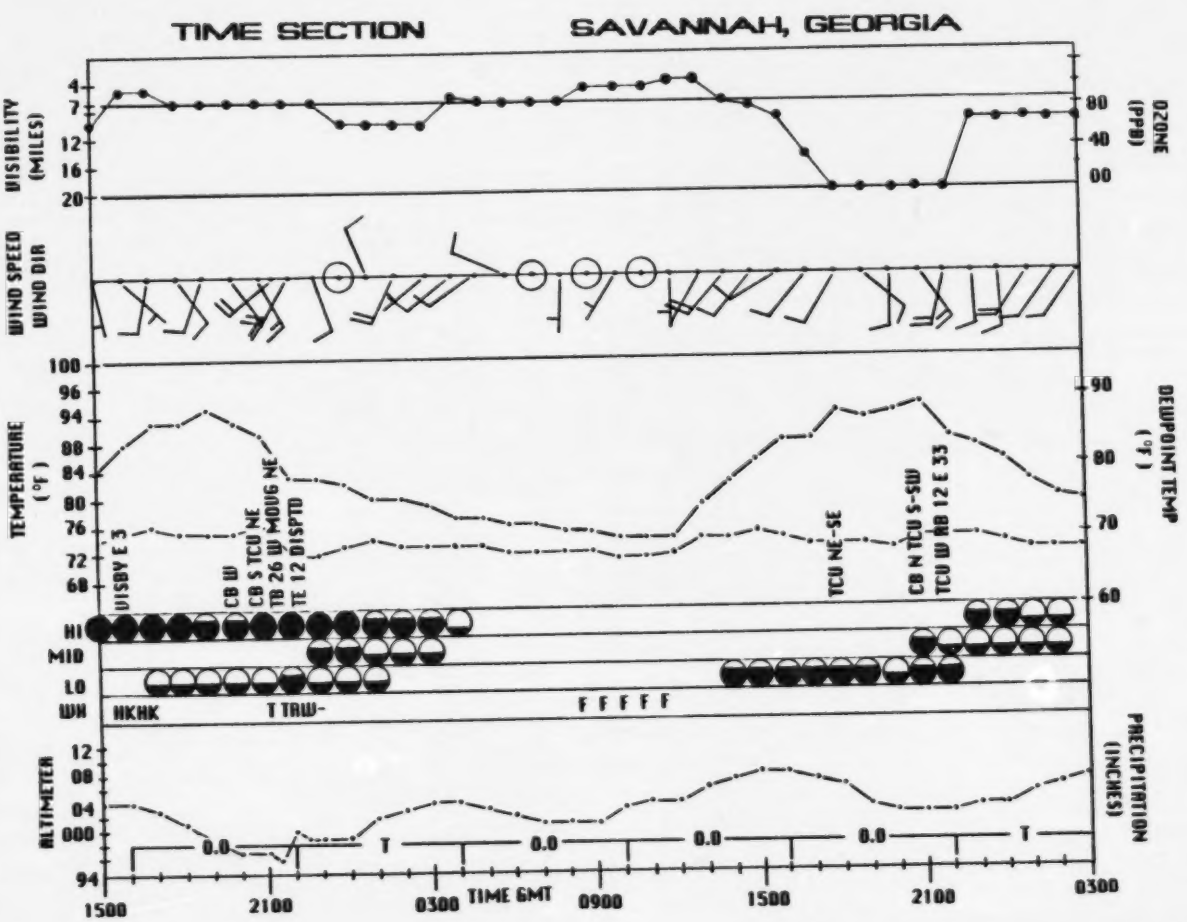

Figure 11. Time section for Savannah, Georgia, covering the period 0900, 13 August 1980 through 2200 EST, 14 August 1980. Notice the marked improvement in visibility that begins at 0900 EST on the 14th of August with visibility approaching 20 miles by 1200 EST.

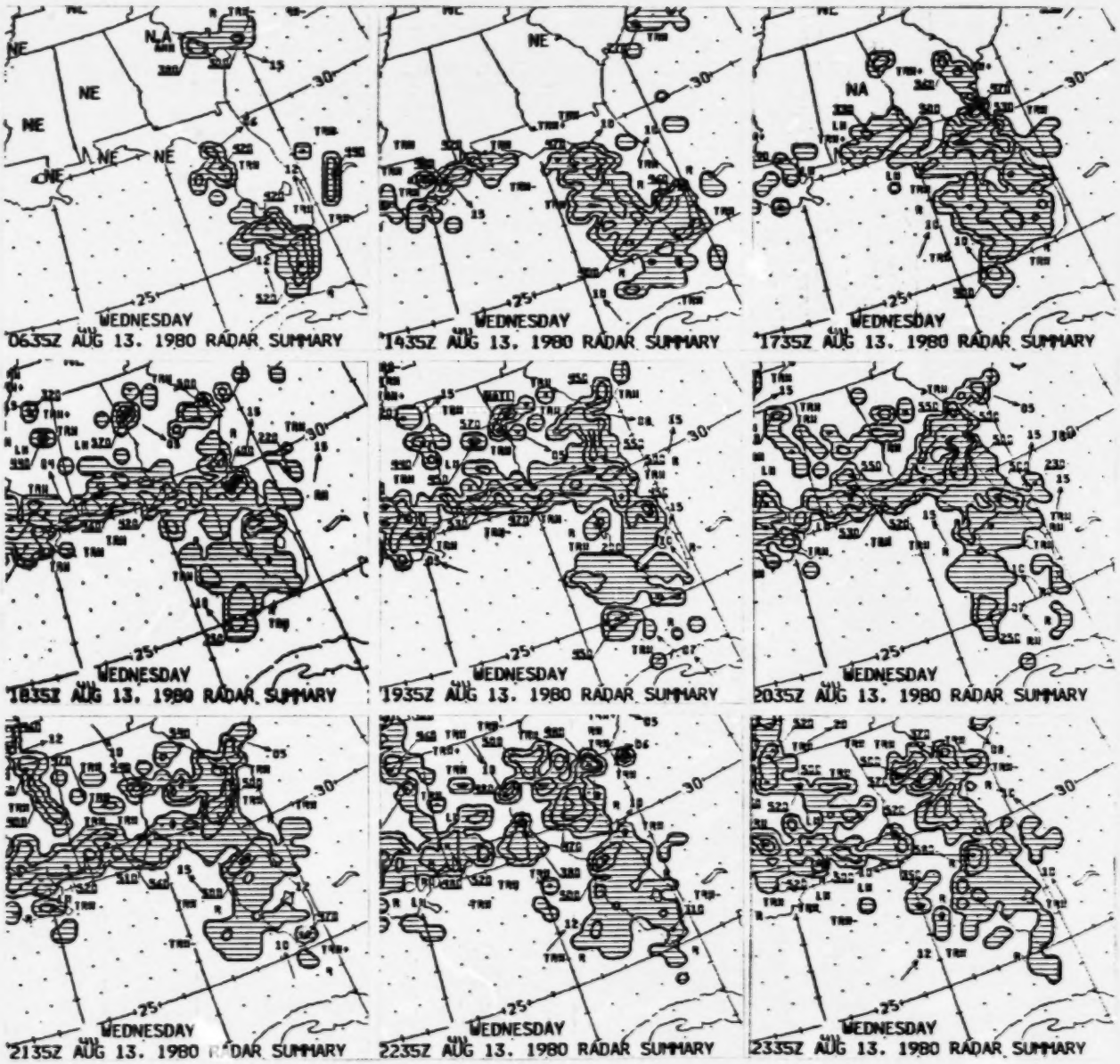

Figure 12. A mosaic comprised of hourly composite MDR (manually digitized radar) weather radar reports as transmitted over the NAFAX facsimile circuit from 0635 GMT to 2335 GMT 13 August 1980.

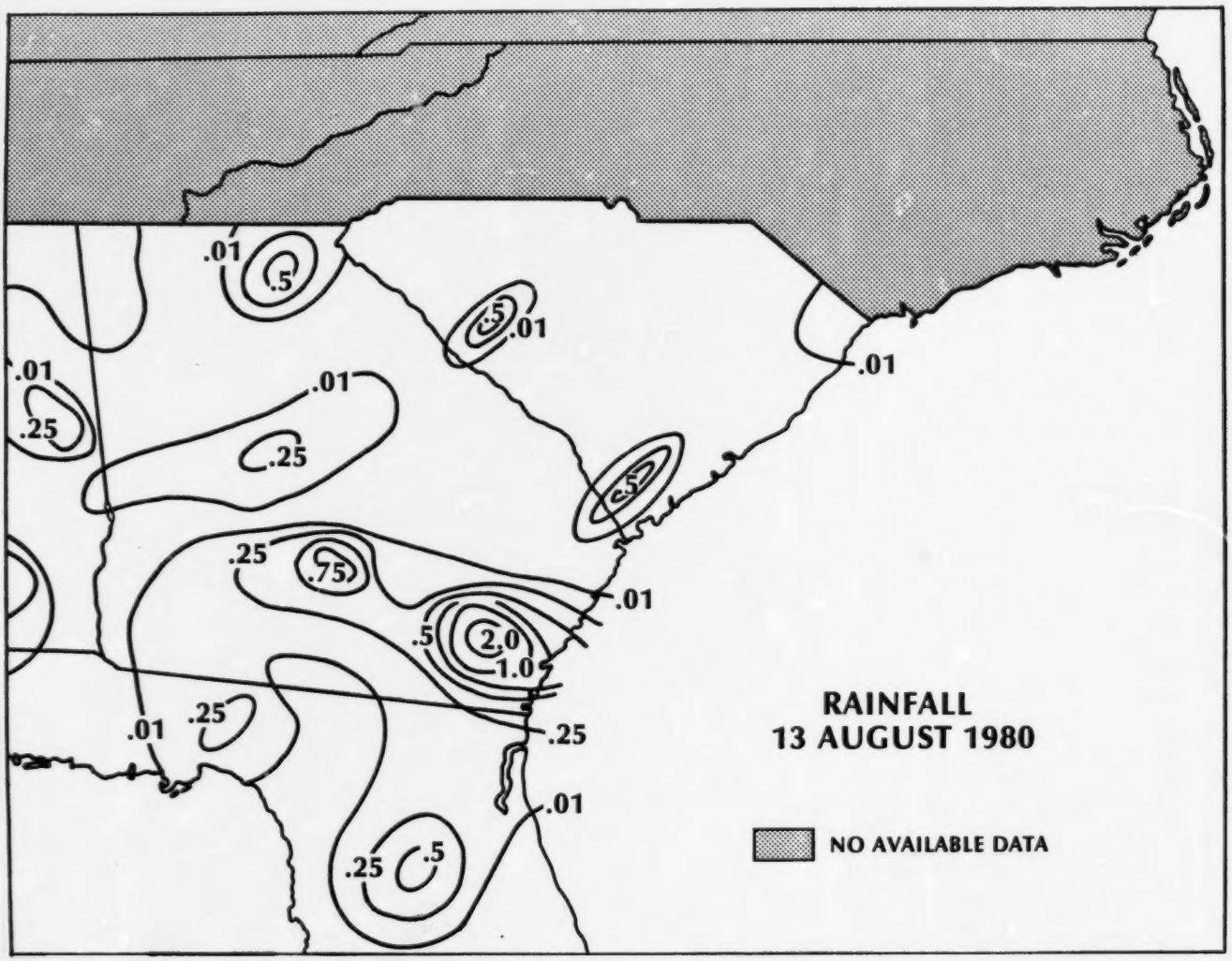

Figure 13. Accumulated rainfall within the project study area from 13 August 1980.

Hourly mesoanalyses were prepared using the techniques of classical mesoanalysis, as detailed by Fujita (1963). All hourly surface weather reports, radar summaries, and GOES were analyzed from 2100 GMT 13 August to 0000 GMT 14 August, and are presented in Figures 14-17. Four parameters were analyzed. These were: (1) surface wind streamlines with MDR radar echoes superimposed, (2) surface altimeter analysis (with 0.02" isobars which approximately equal 0.67 mb), (3) temperature isotherms (every 2° F or 1.2° C), and (4) visibility isopleths in kilometers.

Other mesometeorological features were present in addition to the thunderstorms. A sea breeze front extended the length of the Atlantic coastline and probably played a role in thunderstorm development in northern Florida. Ocean temperatures were approximately 83° F (29° C) and inland temperatures were in the mid-90° F (35° C) range or above. Also, a weak low pressure region was present in mid-Georgia. This may have been a "heat low" associated with the very high temperatures present in the interior of Georgia on 13 August.

At 2100 GMT (Figure 14a), the streamlines illustrate the overall flow from the south (south of the stationary front), with perturbations due to the sea breeze front, heat low, and thunderstorm complexes near Tallahassee and Jacksonville. The heavy barbed lines indicate analysed locations of gust fronts. Isobaric analyses (Figure 15a) demarcate the pressure surges associated with the rain-cooled downdrafts of these thunderstorms. The temperature field also sharply delineates the mesoscale cold dome produced by the thundershowers (Figure 16a). Visibilities throughout Georgia and the Tidewater are generally 11 mi (18 km) or less (Figure 17a). The pocket of 16+ km visibility in the center of Georgia was probably a CARE, produced by a large isolated thunderstorm in that region during the morning of 13 August.

By 2200 GMT (Figures 14b-17b) the thunderstorms near Jacksonville had expanded, with a gust front extending north of Alma to near Savannah. The pool of cooler, drier air produced by the thunderstorm is apparent in Figure 16b. Due to rain and fog within the active thunderstorm mesohighs, little can be ascertained at this hour as to any possible CARE formation. Note though, a region of 16+ km visibility is associated with a weakening thunderstorm cluster in northwest Georgia.

By 2300 GMT (Figures 14c-17c) the two major mesohighs had merged into an even larger system. By 0000 GMT (Figures 14d-17d) the cool air had expanded to cover the area from Beaufort, South Carolina to Tallahassee, Florida. During the period from 2200 to 2300 GMT, the high visibility air (24+ km) associated with a newly emerging CARE became evident (Figure 17c). The gust front had now become the boundary between a CARE and the undisturbed polluted PBL.

In summary we suggest that a CARE resulted from these non-severe, but vigorous air mass thunderstorms over southeastern Georgia and northern Florida on 13 August 1983. These storms are located near the lower end of a size spectrum of mesoscale convective precipitation systems which range from massive MCCs to small isolated thunderstorms.

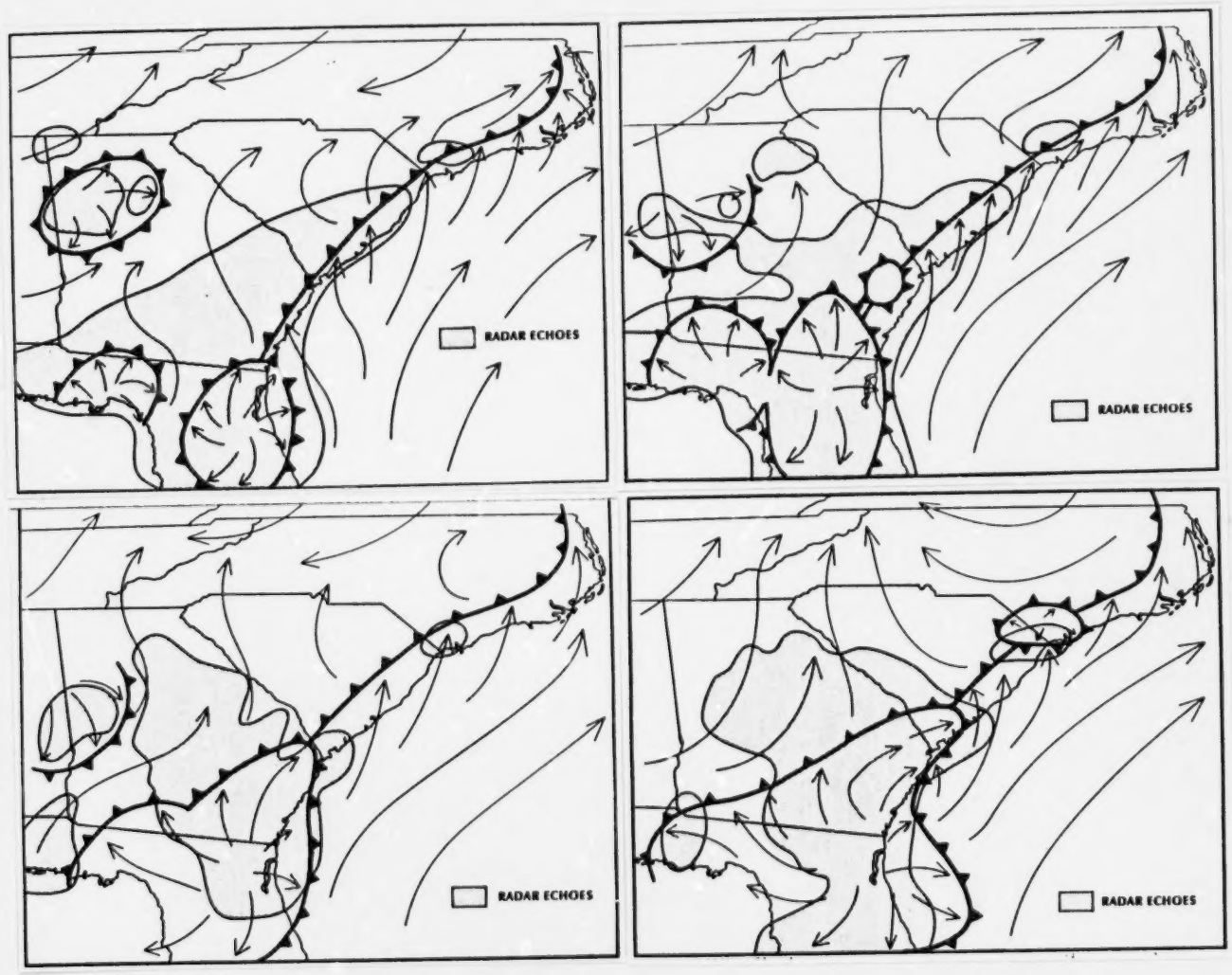

Figure 14a(upper left). Surface winds streamlines and MDR derived radar echoes for 2100 GMT, 13 August 1980. Mesoscale fronts are shown with heavy lines and include both the Atlantic coastal sea breeze and thunderstorm mesohigh boundaries. (14b, upper right) for 2200 GMT, 13 August 1980. (14c, lower left) for 2300 GMT, 13 August 1980. (14d, lower right) for 0000 GMT, 14 August 1980.

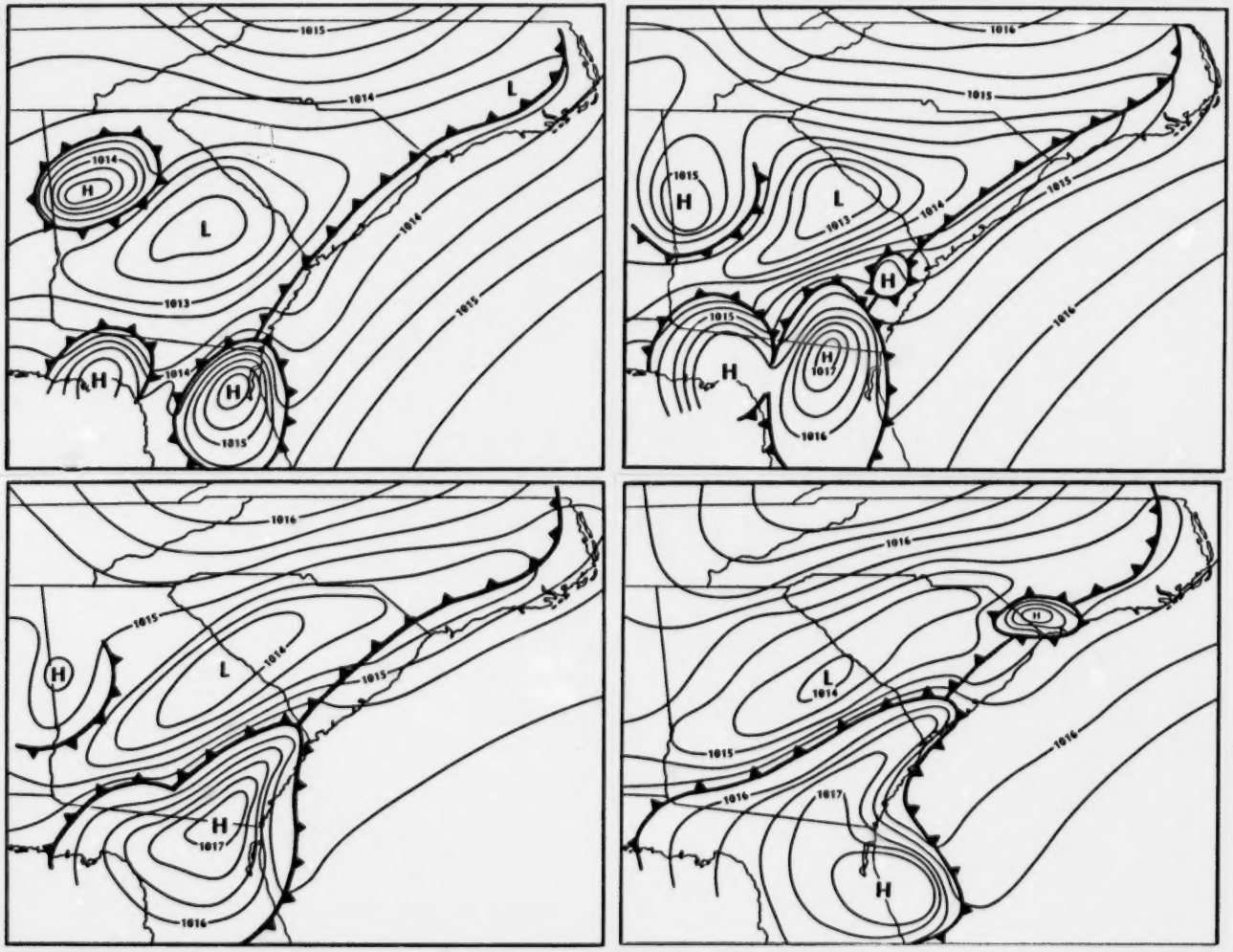

Figure 15a. (upper left) Surface pressure pattern, 0.67 mb isobar interval at 2100 GMT, 13 August 1980. 15b. (upper right) Same, for 2200 GMT, 13 August 1980. 15c. (lower left) Same, for 2300 GMT, 13 August 1980. 15d. (lower right) Same, for 0000 GMT, 14 August 1980.

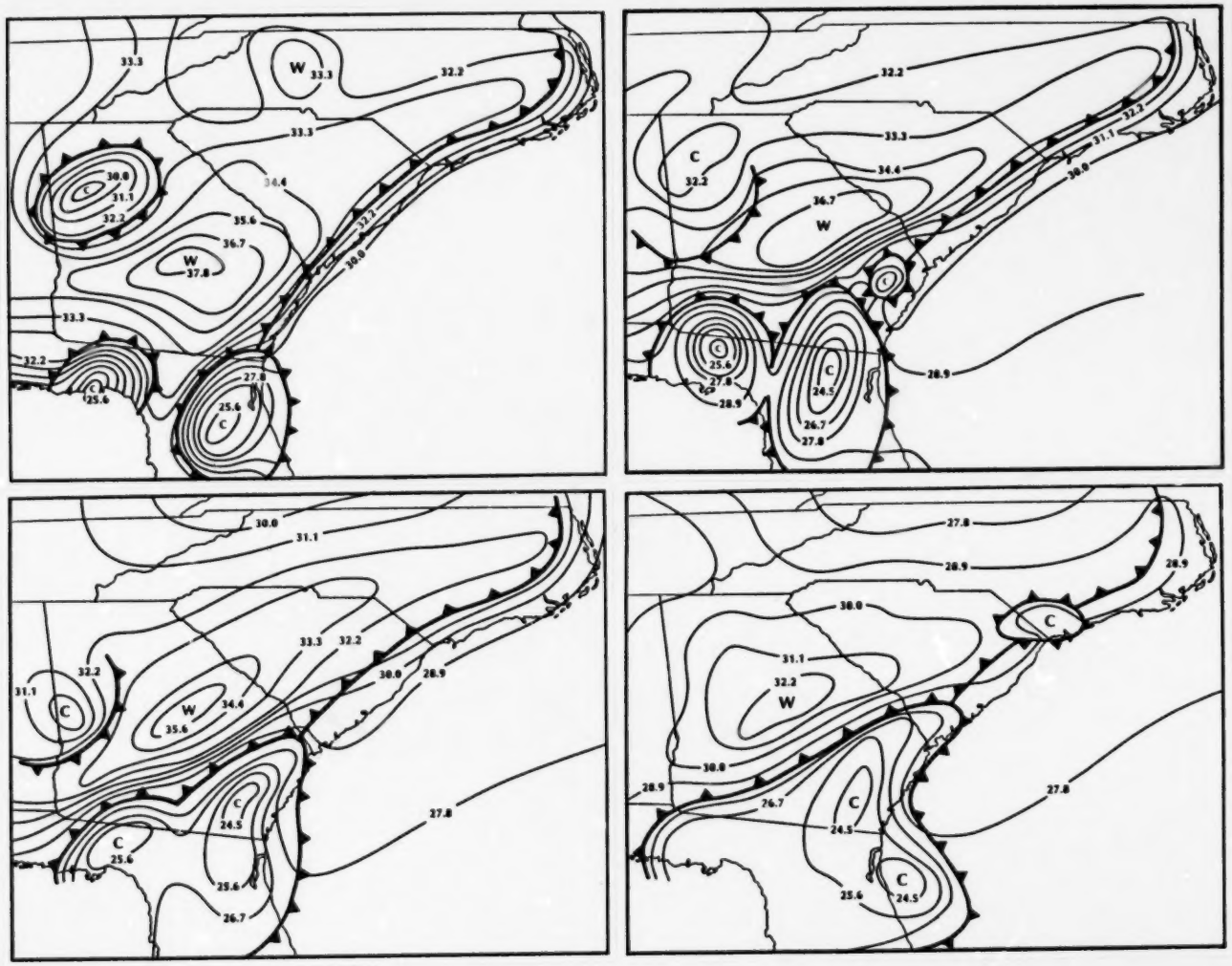

Figure 16a. (upper left) Surface temperature patterns associated with thunderstorm mesosystems and sea breeze fronts, at 2100 GMT, 13 August 1980. 16b. (upper right) Same, for 2200 GMT, 13 August 1980. 16c. (lower left) Same, for 2300 GMT, 13 August 1980. 16d. (lower right) Same, for 0000 GMT, 14 August 1980.

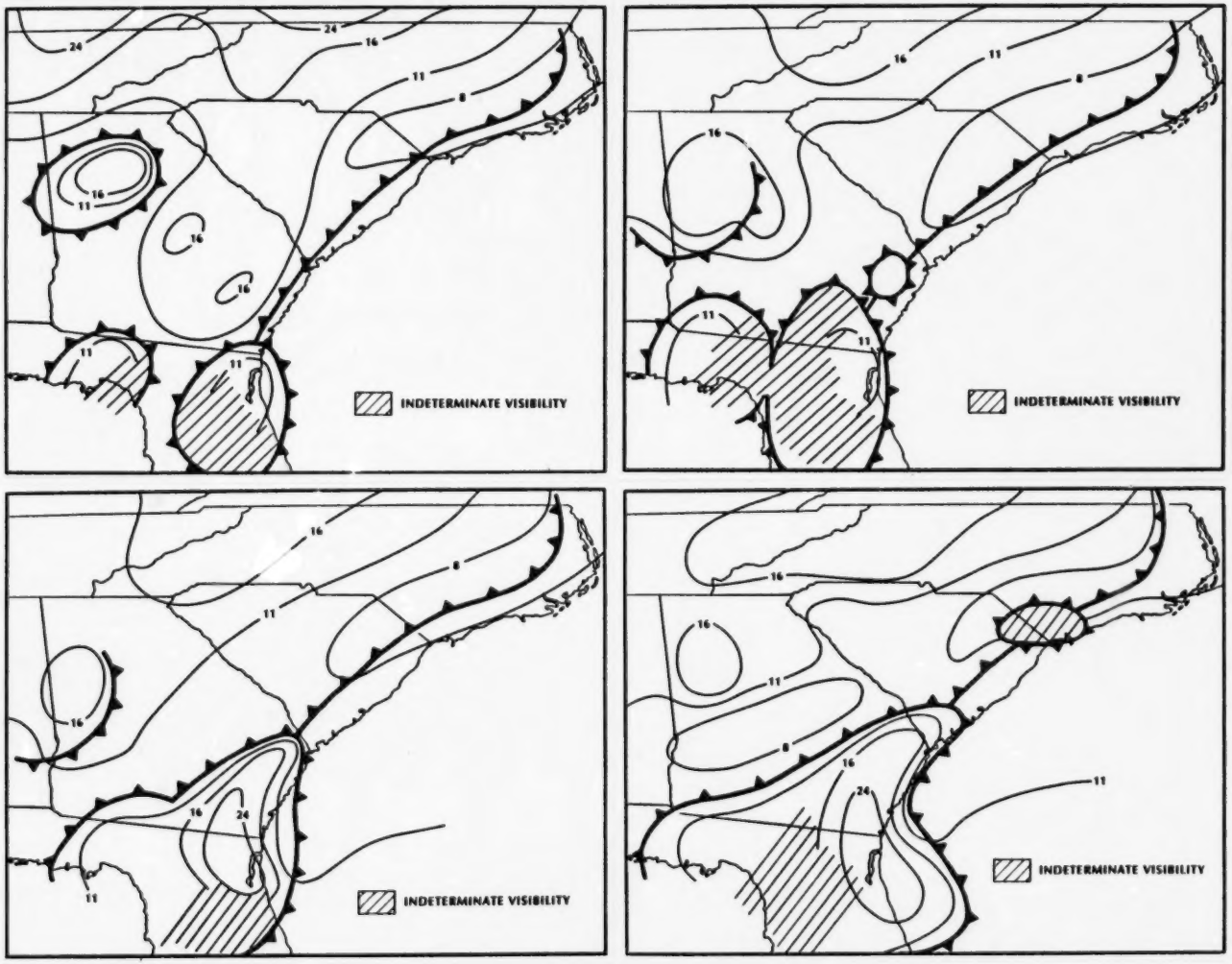

Figure 17a. (upper left) Surface visibility data in km, with areas in which rainfall haze or fog are shown as hatched line on 2100 GMT, 13 August 1980. 17b. (upper right) Same, for 2200 GMT, 13 August 1980. 17c. (lower left) Same, for 2300 GMT, 13 August 1980. 17d. (lower right) Same, for 0000 GMT, 14 August 1980.

Following the procedures of the case studies of an MCC and squall line (Lyons, Calby, and Keen, 1985), the impact of these air mass thundershowers on the polluted PBL were examined. Figure 24 shows the change in visibility during the 24 hour period beginning 1800 GMT, 13 August 1980, and ending 1800 GMT, 14 August 1980. Since a portion of the CARE was over the Atlantic by 14 August, GOES satellite images (Figures 18-19) were used to estimate the over-ocean visibility contours. The area of visibility change of 5 km (3 mi) or greater was 57,600 km^2. The average change in visibility was 7.6 km (4.8 mi). No explicit measurements of mixing height were available, but sounding data from Athens, Georgia and Charleston, South Carolina were used to estimate an average mixing depth of 900 m.

The relationship between atmospheric turbidity, expressed as a backscattering coefficient b_{scat}, and sulfate has been proposed to take the form,

$$b_{scat} = a + cX \qquad (1)$$

where b_{scat} is expressed in units of $10^{-4}m^{-1}$ and X is the total sulfate aerosol mass concentration (ug/m^3). Patterson et al. (1979) proposed values of a = 1.3 and c = 0.17, while Leaderer et al. (1981) suggested a = 0.48 and c = 0.088. The conversion between regional visibility and b_{scat} is given by the familiar Koschmieder relationship,

$$b_{scat} = 24.3 / V \qquad (2)$$

where V is in statute miles. Using the above equations and calculating visibility/sulfate relationships, neither give particularly satisfying results. The Patterson formulation disallows any significant sulfate aerosol mass at regional visibilities greater than about 20 miles, whereas the Leaderer curve results in concentrations which appear somewhat high, especially at large b_{scat} values. Since the Leaderer data were developed using largely New York City data to estimate c, mean data from a variety of sites in the eastern United States reported in Leaderer et al. (1981) were averaged, providing a c of 0.10 which is somewhat more in line with the author's experience as to visibility/sulfate intercomparisons. In all likelihood the proper function is neither constant nor linear. However, this provides at least a reasonable first approximation as to the changes in atmospheric sulfate aerosol concentration due to the passage of the MCS at a site.

Using the above equation, the average volumetric decrease of sulfate aerosol concentrations within the CARE can be estimated. The average visibility change and the depth of the CARE (assumed equal to the mixing depth) is employed. The

TABLE 1

COMPARISON OF THE IMPACTS OF VARIOUS SIZED MESOSCALE PRECEPITATION SYSTEMS: MCC, SQUALL LINE, AND AIR MASS THUNDERSHOWER CLUSTERS

	MCC[1]	SQUALL LINE[1]	AIR MASS
	1-2 Aug 80	1-2 Aug 80	13-14 Aug 80
Area of analysis (km^2)	650,248	636,608	172,800
Area receiving rain (km^2)	286,700	223,000	36,460
Average rain depth (cm)	0.82	0.96	0.48
Area receiving rain (%)	47	35	28
Total mass of rain ($x10^{10}$ kg)	236	215	17.5
Area with vis. change (km^2)	467,527	297,657	57,600
Area with vis. change (%)	77	47	33
Average vis. change (km)	13.3	5.9	7.6
Average vis. after rain (km)	19.5	12.6	18.4
Depth of mesohigh (m)	1500	600	900
Avg. vol. SO_4 change(ug/m^{-3})	38.3	26.9	14.8
Total displaced SO_4 ($x10^6$ kg)	26.8	4.8	7.7
Max. SO_4 conc. in rainwater (mg/l)	11.35	2.24	3.38
Max. SO_4 wet deposition (mg/m^2)	93.4	21.6	16.2

(1) From Lyons, Calby, and Keen (1985)

details of the technique are discussed in Lyons and Calby (1984). The average volumetric sulfate aerosol displacement was calculated to be 14.8 ug/m^3. The total mass of sulfate displaced to form the CARE was 0.8 x 10^6 kg. This is a factor of 50 times less than displaced by the MCC of 2 August 1980.

It was not possible to estimate the rainfall volume over the ocean with these data and no attempt was made to do so. Thus, the total storm precipitation estimates used in this study probably err on the low side. Note, however, that the isohyets (Figure 13) do indicate that most of the rainfall occurred just west of the coastline. The average depth of rainfall over land was 0.48 cm and covered 36,460 km^2. If we assume that all particulate sulfate was washed out in the rain, the average rainwater concentration of SO_4 would have been 3.38 mg/l. Similarly, the average SO_4 deposition would have been 16.2 mgm^{-2}.

An examination of Table I shows that the air mass thunderstorm cluster does represent a smaller perturbation to the polluted PBL than either the MCC or squall line, as was expected. The area experiencing a visibility increase was approximately eight times less than that caused by the MCC, and three times less than the CARE from the squall line. The total displacement of SO_4 mass from the polluted PBL, 7.7 x 10^5 kg, is substantially smaller.

However, it can also be noted that while smaller in area and total mass displacement, the impact of the air mass thunderstorm cluster was as "intense" as the large MCS types. The average visibility change of 7.6 km was greater than for the squall line of 2 August. Similarly the resultant visibility of 18.4 km was only slightly less than for the MCC case. The average volumetric sulfate aerosol decrease was less than the 2 August case, most likely due to the substantially less polluted nature of the antecedent air mass.

Regional ozone patterns were also impacted by the CARE. Figures 20-21 show the maximum hourly ozone concentrations (in ppb) over the southeast on 13 and 14 August respectively. The scarcity of monitoring sites (less than two dozen) make it difficult to ascertain any strong patterns due to the comparatively small size of the CARE. An area of substantially reduced maximum O_3 levels (10 ppb vs. 80 ppb) is found along the Georgia - South Carolina coast on 14 August. This is most likely the signature of the eastward portion of the CARE, now transported offshore.

It is becoming increasingly certain that CAREs of various sizes are routinely produced by convective storm systems with a considerable variety of types and magnitudes.

SATELLITE DETECTION OF THE CARE OF 14 AUGUST 1980

The extent and magnitude of the CARE over Georgia, the Carolinas, and adjacent ocean areas was evaluated using GOES satellite digital VISRR brightness values which were archived as part of PEPE/NEROS-80. These brightness values were obtained using the McIDAS (Man Computer Interactive Data Access System) at the Space Science and Engineering Center of the University of Wisconsin-Madison (Wash and Whittaker, 1980). This procedure is discussed in more detail by Lyons

Figure 18. GOES visible image, 2 km resolution, DB5 sector, showing cloud and patterns over the southeast United States at 1430 GMT, 14 August 1980. Notice the area of reduced turbidity east of the South Carolina coast.

Figure 19. GOES visible image, 2 km resolution, DB 5 sector, 2130 GMT, 14 August 1980, showing convective clouds and turbidity patterns over the southeast United States. Notice the extensive areas of reduced turbidity east of the South Carolina coastline.

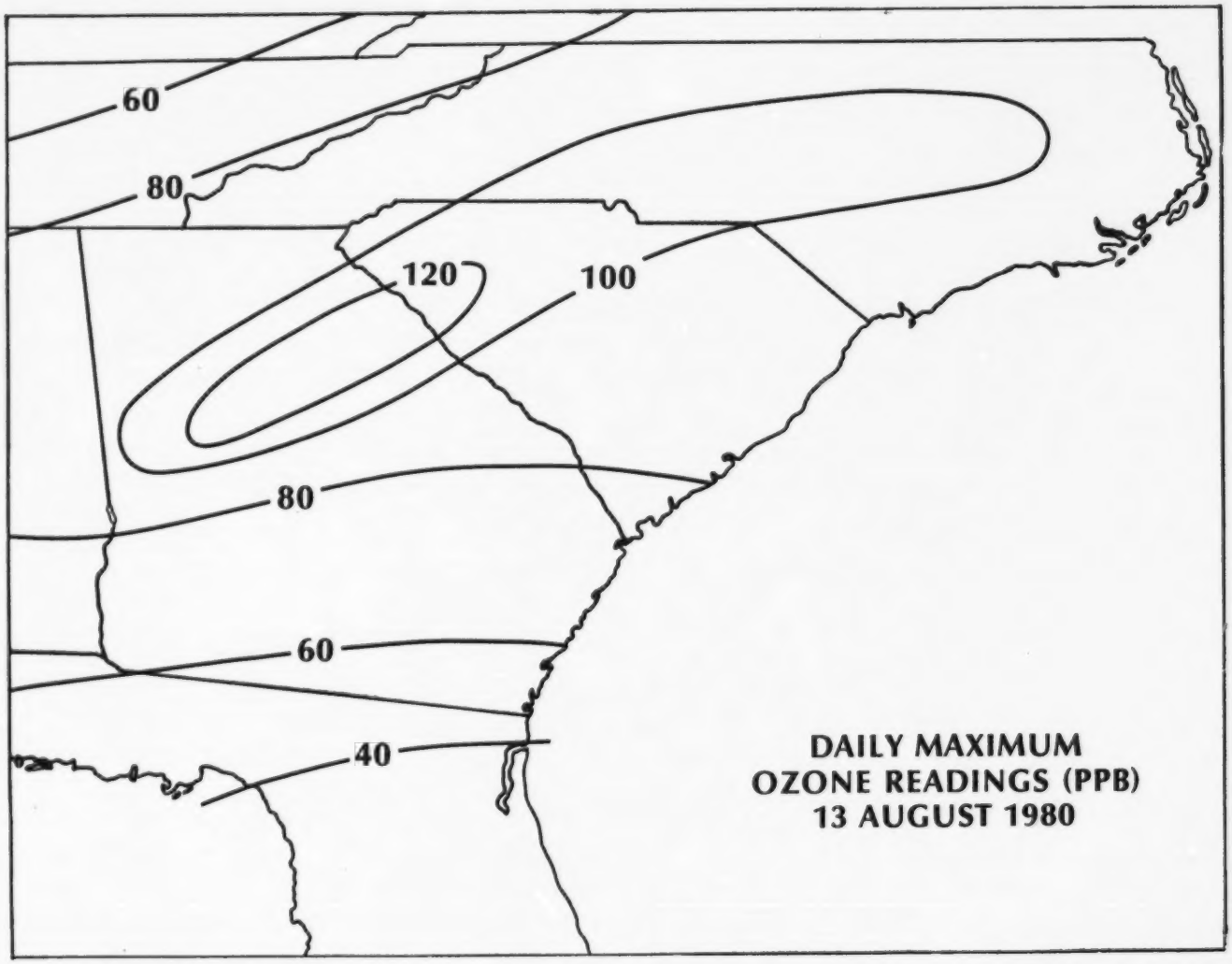

Figure 20. Isopleths of maximum one hour surface ozone reports, from monitors in the study area, 13 August 1980. Contours are in parts per billion (ppb).

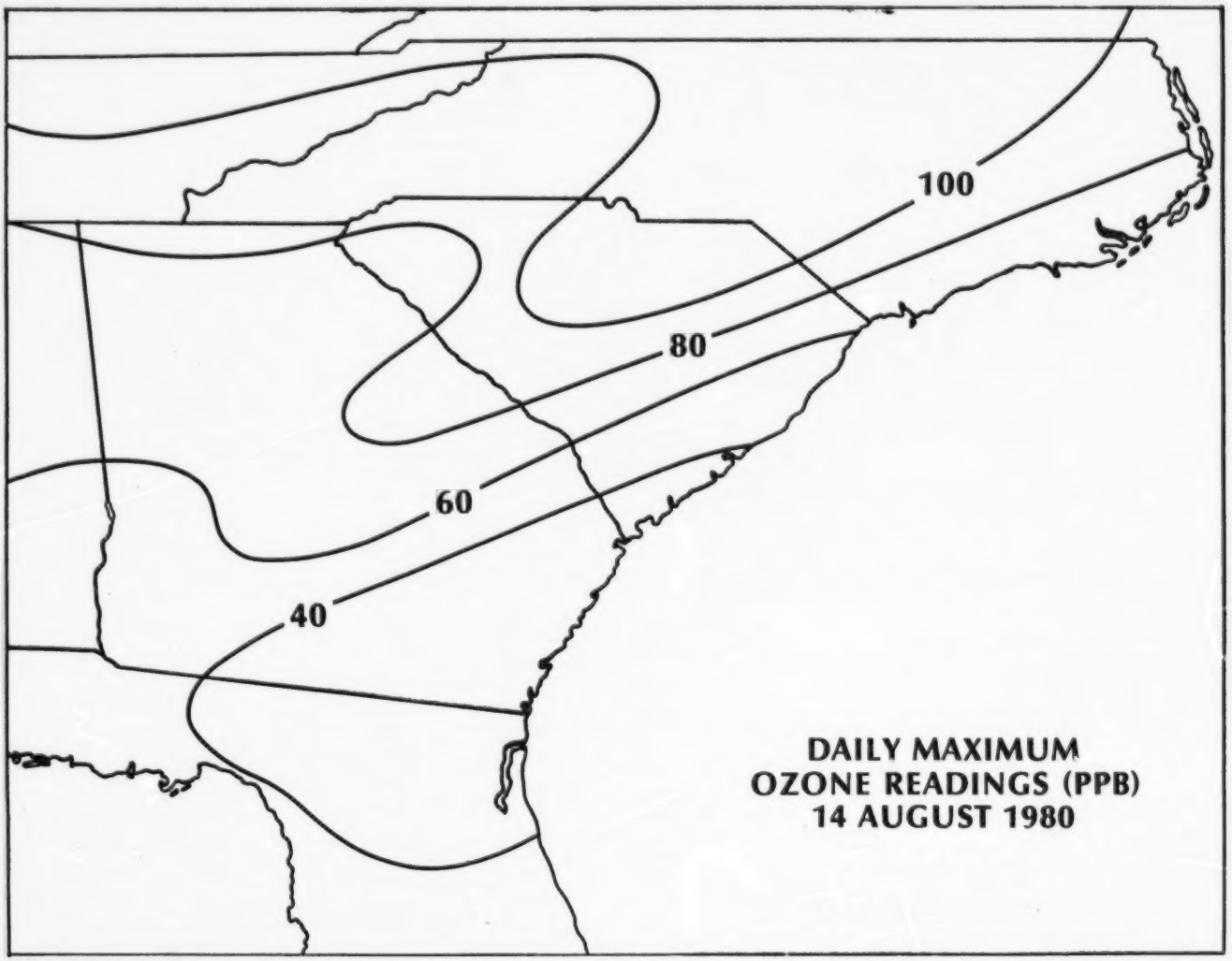

Figure 21. Same as Figure 23, but for 14 August 1980.

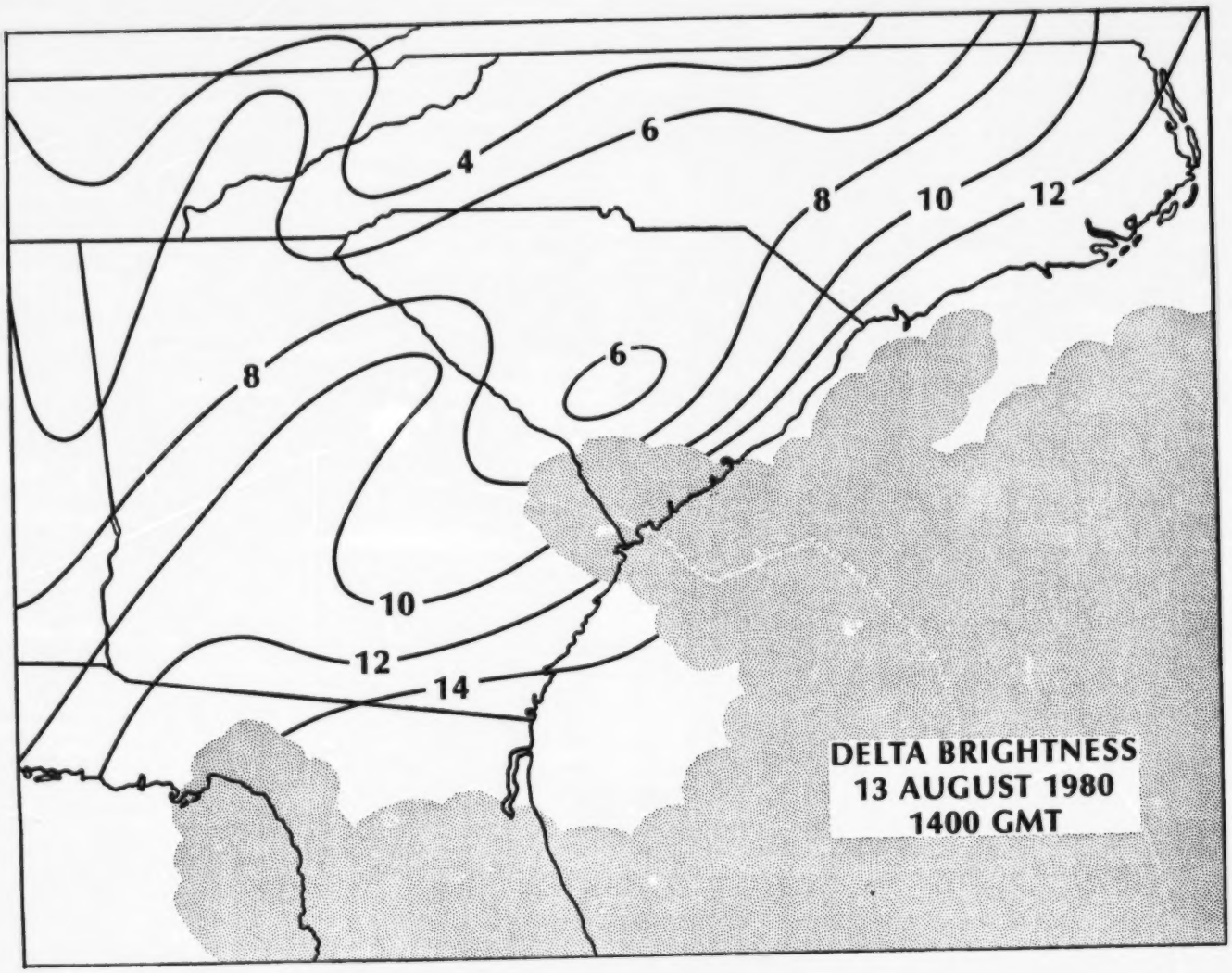

Figure 22. Isopleths of delta brightness levels, derived from the McIDAS system, using digital satellite imagery for 1400 GMT, 13 August 1980. Areas with cloud cover shown in stipple.

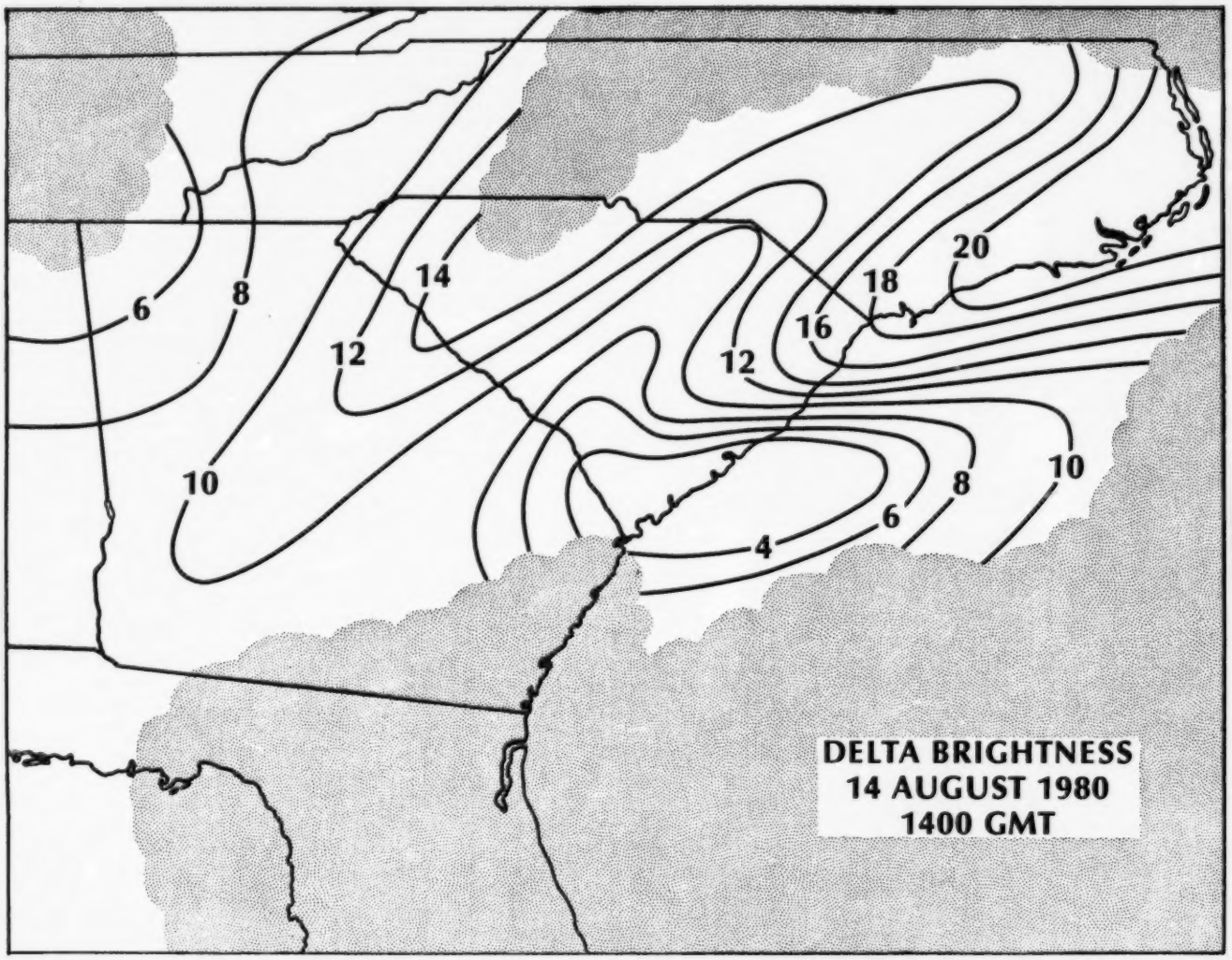

Figure 23. Same as Figure 22, but for 14 August 1980.

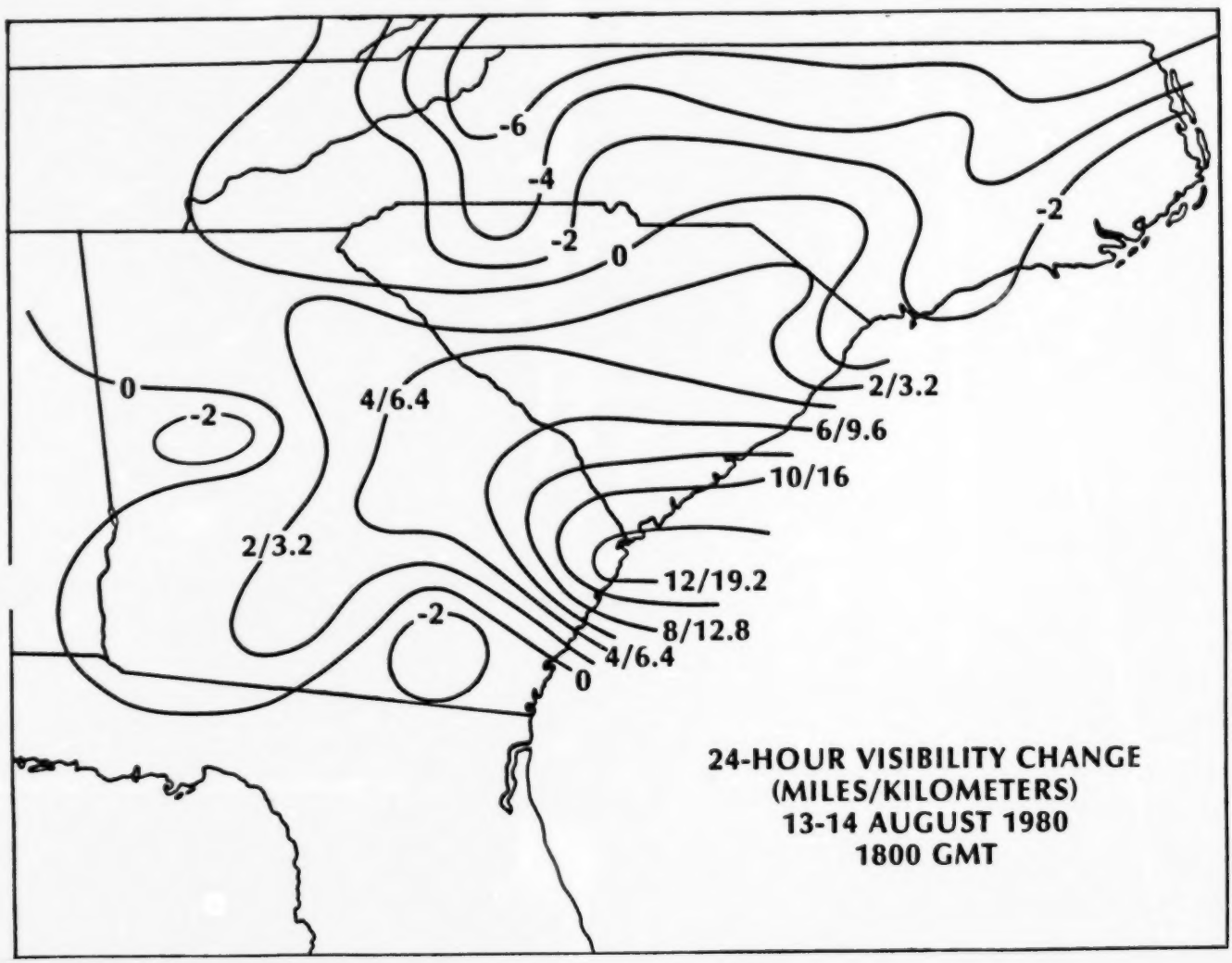

Figure 24. Change in visibility (statute miles/kilometers) reported by National Weather Service first order stations in the study area from 1400 GMT, 13 August to 1400 GMT, 14 August 1980.

and Calby (1983) and Calby (1983). Digital brightness counts were archived for 190 selected areas across the eastern United States at 1400 GMT for each day of the PEPE field study (15 July - 15 August 1980). The digital brightness count as determined by the GOES-East sensor is proportional to the square root of the scene radiance. Conversion of the digital counts to actual radiances was not attempted in this study. Instead the digital counts were examined for relative differences. A delta brightness value was determined at each monitoring site by subtracting the site specific minimum or cloud and haze free minimum brightness value from the brightness measured on the given day at each site. The lower the delta brightness value, the less turbid the air mass.

Unfortunately, cloud contamination limited the usefulness of the satellite data on both 13 and 14 August. But enough data points were obtained to support the arguments of the previous sections. Figures 18 and 19 show the GOES visible images for 1430 GMT and 2130 GMT, 14 August 1980. Though cloudiness is scattered throughout the region, a distinct CARE is visible (especially in the original) east of the Georgia-South Carolina border. The delta brightness values obtained at 1400 GMT on 13 and 14 August are analysed in Figures 22 and 23 respectively. On the morning of 13 August note the low delta brightness values, which indicate the clean air north of the cold frontal zone in North Carolina and Tennessee. Southern Georgia, however, is still "bright", or hazy, due to the developing PEPE in the region. By 14 August (Figure 21), much of southern North Carolina had become increasingly "brighter" as the PEPE continued to build. The large region of low delta brightness values extending eastward from the South Carolina-Georgia border is very noticeable. This is the signature of the CARE from the thunderstorm clusters of the prior afternoon. As can be seen in Figure 19, this CARE remained largely unchanged in size and shape while moving northeast during 14 August. The generally stable nature of the atmosphere over the ocean is in part responsible for the rather long lifetime of this feature.

SECTION 6

CASE STUDY: 29-30 JUNE 1975

During the last week of June and the first week of July, 1975, a massive PEPE occurred over the eastern United States. Figure 25 shows the extensive hazy area associated with this PEPE stretching from the Mississippi River more than 1500 km east of the Atlantic coast. By 5 July 1975 (Figure 26) the eastern United States from northern Florida to the southern Great Lakes was still largely engulfed in anthropogenic haze. This episode has been studied in great detail by Lyons and Husar (1976), and Lyons (1980). In the midpoint of the episode, on 30 June, visibility dropped as low as 2.5 mi (4 km) in the St. Louis area. Since mid-day humidities were in the 40% range, hygroscopicity was not a question. Nephelometer readings both in urban St. Louis and 30 km away showed less than 30% variability, indicating no important urban component. Total sulfate aerosol was measured at approximately 35 ug/m^3, 40% of which was found to be sulfuric acid aerosol. Measurements also showed that the vast majority of the aerosols were in the .05 to 1.0 micrometer diameter range. Limited sulfate measurements made across the country on 29-30 June showed that within the area of haze as seen on the satellite picture (Figure 27), sulfate readings ranged from 17 to as high as 80 ug/m^3. Numerous air quality monitoring sites reported peak maximum hourly ozone values in excess of 160 ppb.

Meteorological conditions during this period were nearly stagnant. The surface analysis at 1800 GMT on 29 June 1975 (Figure 28), is typical of the pattern which was maintained during the episode. Most interesting are computer trajectories, at 600 m AGL, which extend for 36 hours, in six hour increments, beginning at 0000 GMT, 29 June 1975 (Figure 29). Obvious is the slow, but persistent flow from the Great Lakes to the Ohio Valley, then to the Tennessee and Mississippi River valleys and then northwards into the western Great Lakes region. The widespread nature of the episode was dramatically illustrated by analyses of the surface visibility reports made from first order weather stations at 1800 GMT, 29 June 1975. Only those stations which were not reporting obstructions to visibility (rain, fog, dust) and which had dewpoint depressions of 3° F or more were included. The area of lowest visibility clearly corresponds with the brightest and haziest portions of the satellite image in Figure 27.

A closer look at Figure 27 reveals that the milky white haze of the PEPE is not homogeneous. What appears to be thin spots in the haze are visible over portions of southeastern Missouri, Illinois, Indiana, and along the Ohio River Valley. It had long been assumed by the authors that these turbidity discontinuities in fact represented CAREs, the result of mesohighs produced by scattered air mass thunderstorms occasionally developing within the otherwise fair weather high pressure system. An analysis was undertaken to correlate the suspected CARE with the appropriate mesoscale convective precipitation system.

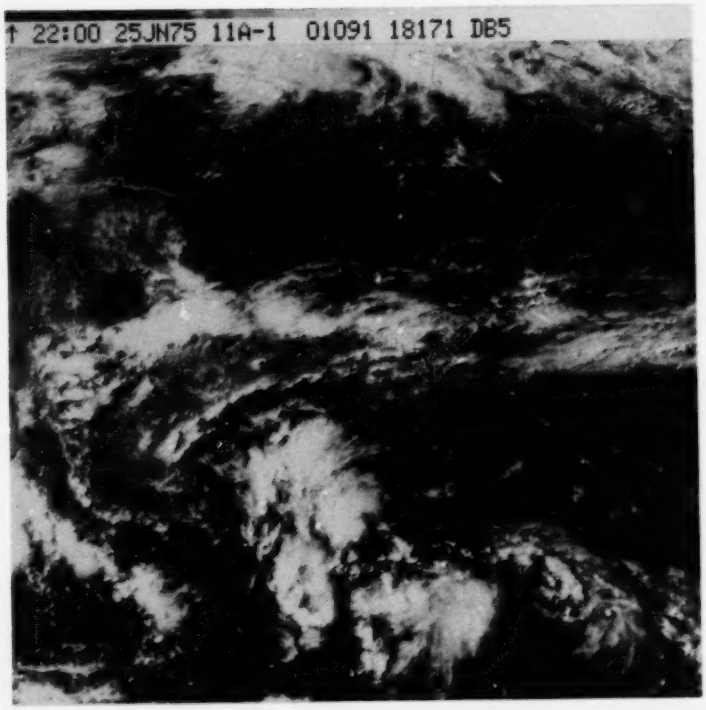

Figure 25. GOES visible image, 2 km resolution, DB5 sector, at 2200 GMT, 25 June 1975. A massive area of turbidity marks a PEPE stretching from the Mississippi River eastward almost 1500 km into the Atlantic Ocean.

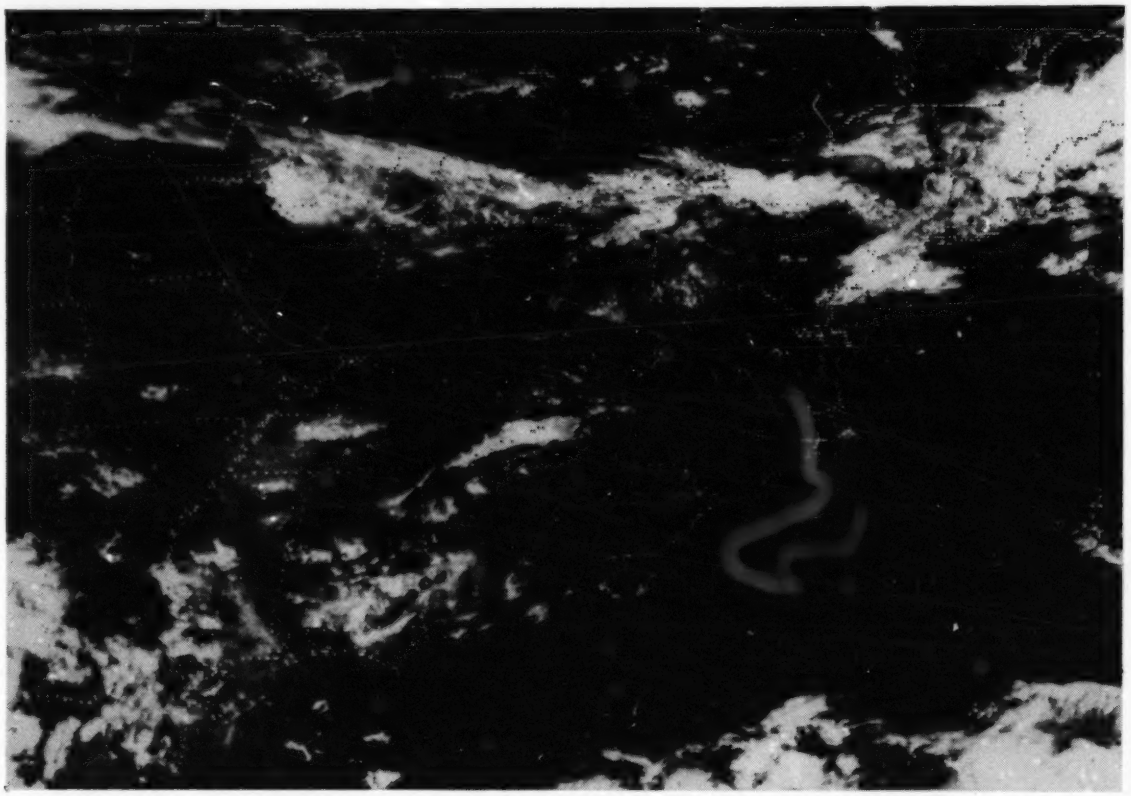

Figure 26. GOES visible image, DB5 sector, 2 km resolution, 1500 GMT, 5 July 1975, showing a large area of turbidity over the eastern United States during the waning stages of the massive two-week long June/July 1975 PEPE event.

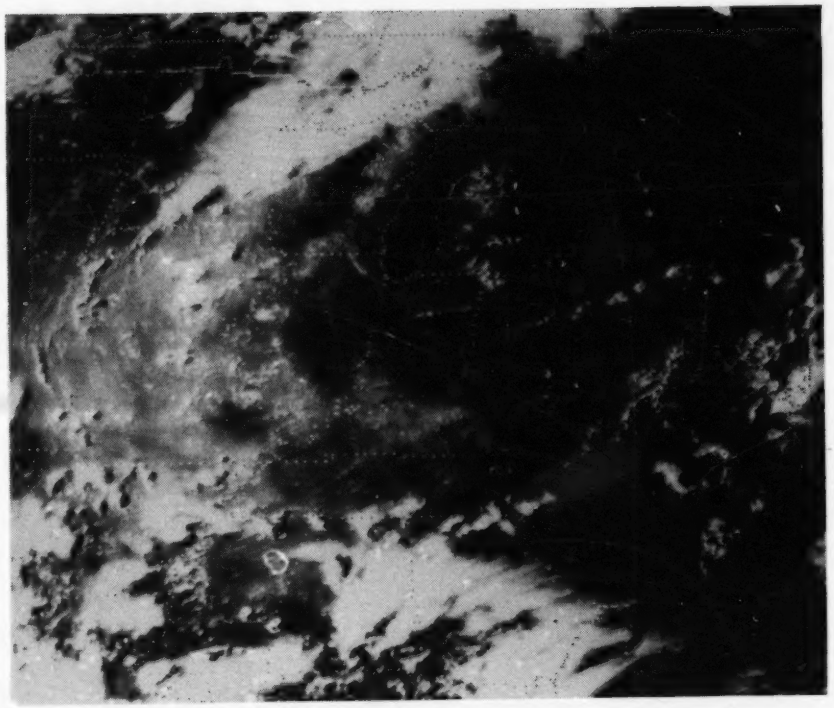

Figure 27. GOES visible satellite image, 2 km resolution, DB5 sector, at 2200 GMT, 29 June 1975. The massive PEPE extends from the Central Plains eastwards to the Atlantic coast. Note in particular the pockets of apparently cleaner air over portions of Missouri, Illinois, Indiana, and the Ohio River Valley. Notice also discontinuity in the turbidity pattern over Lake Michigan.

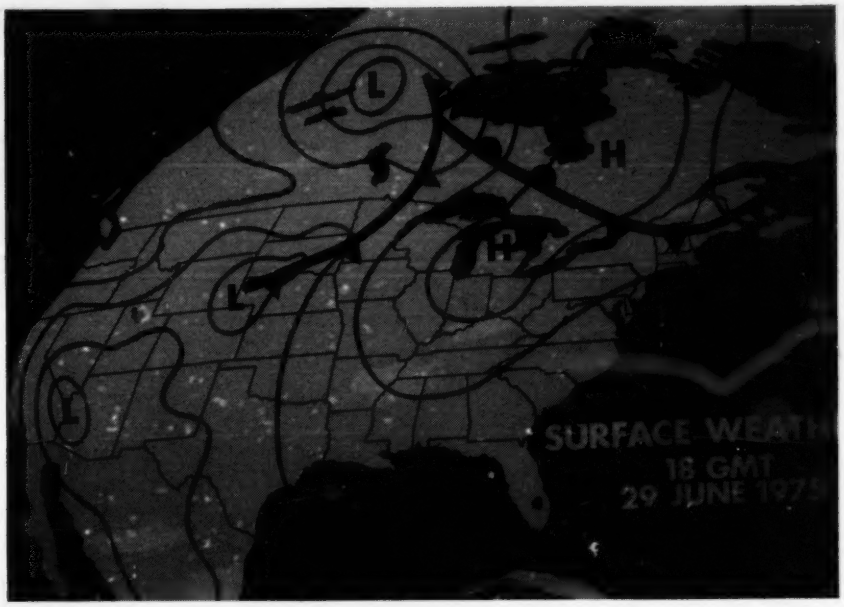

Figure 28. Surface analyses, 1800 GMT, 29 June 1975.

Figure 29. Computed trajectories, at 600 m AGL extending at six hour intervals for 36 hours, beginning 0000 GMT, 29 June 1975.

Figure 30. Analysis of visibility reports (in statute miles), from first order surface weather stations, at 1800 GMT, 29 June 1975. Visibility in portions of Iowa and Missouri dropped to as low as 2 miles.

Archival 10" square GOES image negatives were obtained from National Environmental Satellite Data Information Service for each hour of the two day period. Figures 31 and 32 show tracings of the leading edge of the suspected CARE during the daylight hours. On both days the suspected CAREs were seen to drift with the low-level wind and in a southwesterly direction.

Paper fascimile copies of the hourly National Summary of Radar Reports (the SD chart) were obtained from the National Climatic Data Center. These maps are prepared from manually digitized radar data submitted hourly by each National Weather Service radar station. While very useful for many purposes, MDR has one conspicuous failing. Due to the coding technique, the areal coverage of precipitation is greatly exaggerated since even the smallest thunderstorm automatically fills a 22 mile square box completely. For 28-29-30 June 1975 (Figures 33-35), 24 hour composites of the hourly MDR charts were prepared. There was apparently widespread precipitation indicated in the area. However, indications of apparent coverage can result only from very brief and widely scattered showers. On 28 June, precipitation appeared to be quite widespread over the eastern United States. By 29 June, even in an MDR display, rain had become quite sparse in the general vicinity of the Great Lakes and the Ohio River Valley. The source region of the suspected CAREs. The same pattern held for 30 June 1975. Very little thunderstorm activity, other than extremely small, isolated cells developed in the general vicinity of the CAREs on these two days. Surface precipitation reports (Figure 36) from 27 June 1975 through 0600 GMT 29 June 1975 showed only widely scattered precipitation through the area. In the areas presumed to be upwind of the CAREs as observed on 29 June 1975, only relatively small and isolated patches of precipitation occurred. It became increasingly clear that in spite of a most intense scrutiny of the date, these very distinct CAREs could not be related to specific thunderstorm clusters. This is quite an unexpected result.

After considerable puzzlement, an interesting observation was made. If one examines Figure 31 and especially Figure 32, the suspected CARE outline bears a noticeable resemblance to the shorelines of the Great Lakes which are located upwind. At this point a new hypothesis is formulated. It appears plausible that there may exist a pseudo-CARE, i.e., localized intrusion of lower turbidity air from aloft into an otherwise turbid PEPE region by other than convective precipitation processes. As noted by Lyons and Cole (1976), the synoptic situations during the 28-30 June 1975 period was ideal for the development of intense lake breezes over the Great Lakes. A lake breeze is a highly complex phenomenon. Among other things it results in substantial transport and dispersion of pollutants both on a local and regional scale. This has been studied with the aid of photography by Lyons and Olson (1973) and numerical models (Lyons et al. 1983). Lyons (1970, 1971) documented the intense subsidence which occurs over the Great Lakes during such lake breezes. Thus, while air over land is being continuously mixed upward due to the development of the daytime heated

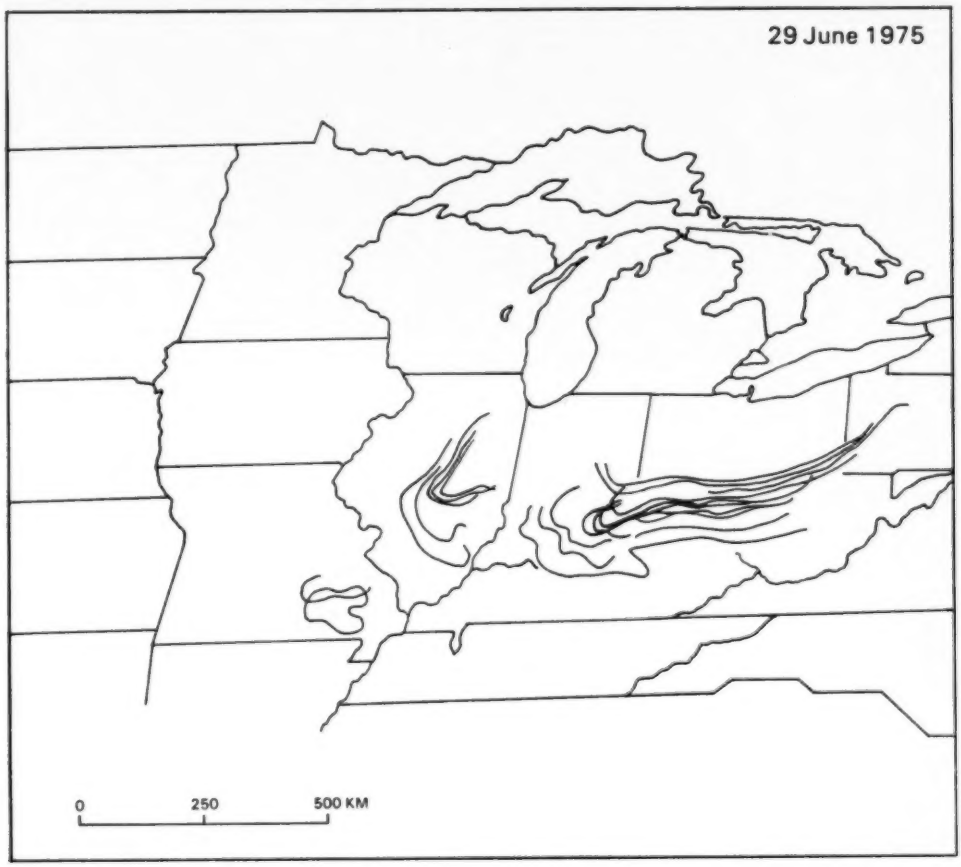

Figure 31. Analysis of the turbidity discontinuities observed in the satellite images on 29 June 1975. Each line indicates the boundary between the clean air and more turbulent air, on the edge of the apparent CARE. CARE boundaries are shown at 1 hour intervals.

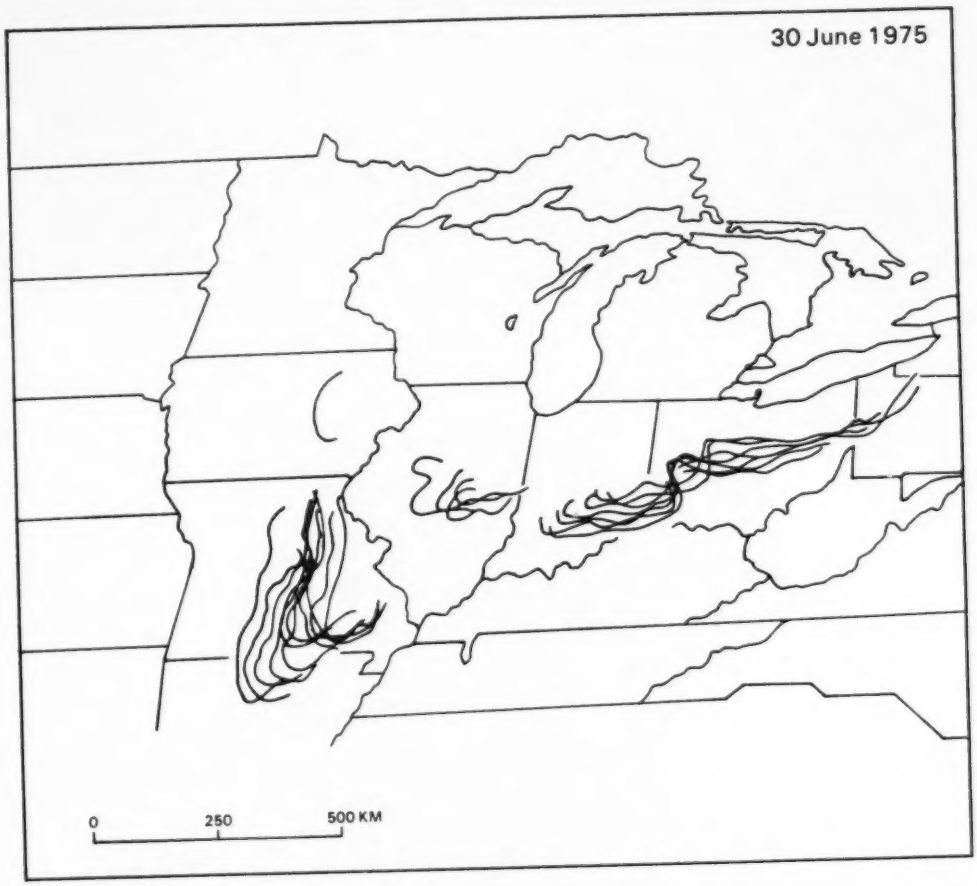

Figure 32. Same as Figure 31, but for 30 June 1975.

Figure 33. Summary of all areas reporting radar echos via MDR generated radar reports for the 24 hour period of 28 June 1975. The area of coverages greatly exaggerates the actual area of coverage since even the smallest thunderstorm 22 mile square area is indicated in blue.

Figure 34. Same as Figure 33, but for 29 June 1975.

Figure 35. The same as for Figure 33, but for 30 June 1975.

Figure 36. Summary of precipitation reports, from 1200 GMT, 27 June 1975 through 0600 GMT, 29 June 1975. Amounts greater than one inch (2.54 cm) are shown in yellow.

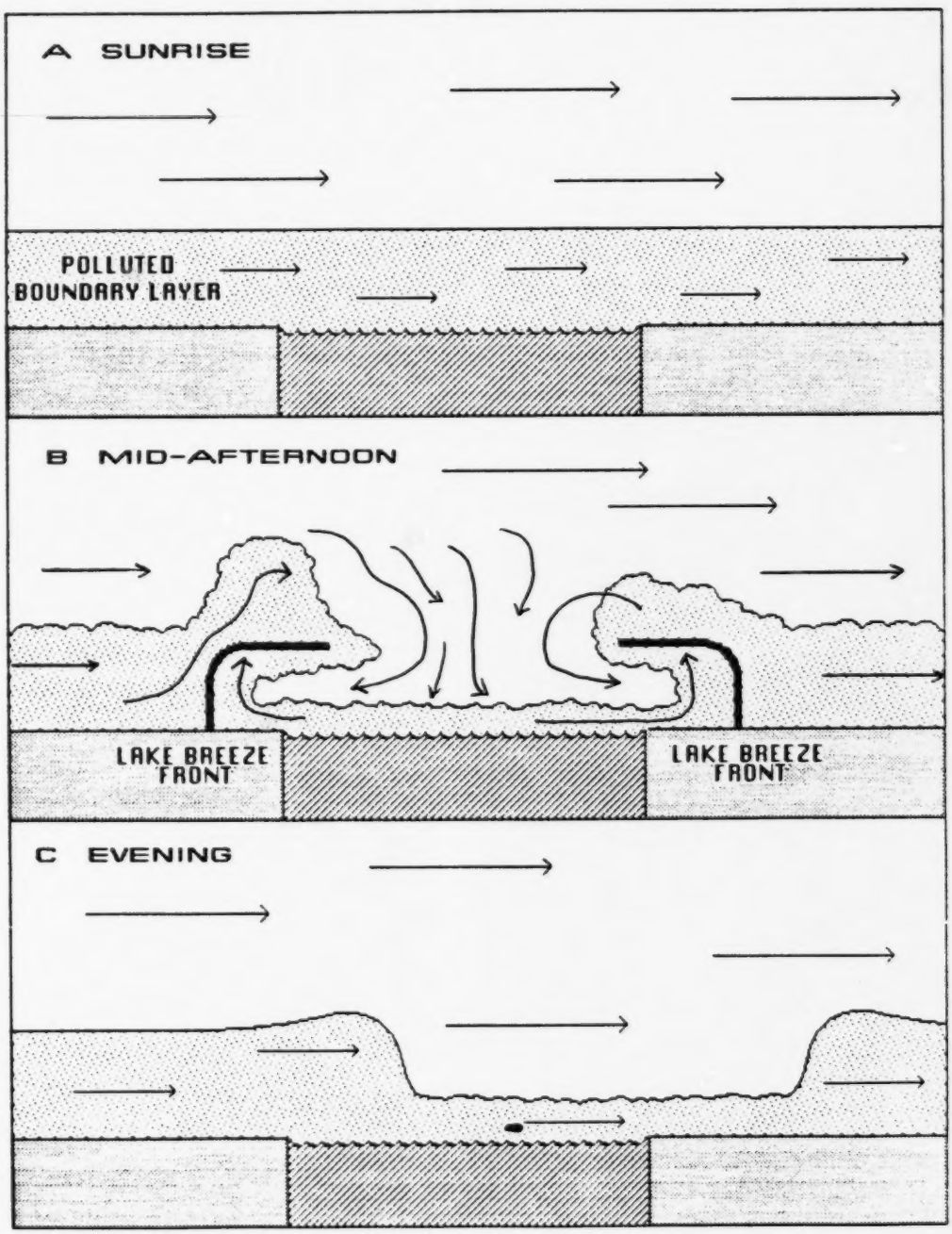

Figure 37. Hypothesized mechanism whereby a pseudo-CARE is generated due to subsidence associated with lake breezes over the Great Lakes. Aerosol matter in the initial uniformly polluted planetary boundary layer is shown in light stippling.

due to the highly divergent surface wind field. The lack of any thermal mixing over the lake further stabilizes the boundary layer over water. Figure 37 illustrates the hypothesized mechanism whereby a pseudo-CARE can be generated over the Great Lakes due to the subsidence associated with a lake breeze. An initially uniformly polluted boundary layer during the early morning hours is drifting with the synoptic flow across the Great Lakes, in this case from the northeast to the southwest. By mid-afternoon, with the establishment of a lake breeze circulation, mixing over land counterbalanced by extreme subsidence over water causes a marked depression in the depth of the aerosol contamination over the lake. By evening, with the cessation of the lake breeze circulation, the aerosol depletion zone drifts inland with the synoptic flow. With the on-set of convective mixing the following morning, the very thin polluted layer is then mixed with essentially clean air above, resulting in dramatically reduced aerosol loading and turbidity and improved visibilities. Aside from the shape, other evidence suggests the pseudo-CARE may, in fact, have been formed by the lake breeze mechanism. The general direction of the boundary layer flow as seen in the trajectory computations, plus the presence of lake breezes over the Great Lakes on these days, both suggest this is a plausible explanation.

SECTION 7

OTHER PSEUDO-CARES

In Section 4 it was shown that the development of a CARE as the result of even smaller scale thunderstorms is a definite and probably frequent occurrence. However, the apparent discovery of the pseudo-CARE suggests that not all low turbidity pockets within PEPE air masses are related to precipitation events. There are a number of phenomena which occur in the dry atmosphere that can possibly depress the mixed layer. If subsidence brings cleaner mid-tropospheric air close enough to the surface , it becomes susceptible to ultimate mixing to the surface itself by thermal convective processes.

Mountain waves are a well known phenomena and appear with considerable regularity over the Appalachian Mountains of the eastern United States (Pecnick and Young, 1984). In general, intensive standing wave activity may develop in the lee of mountains when zonal winds increase with altitude, especially if there is some form of inversion at or above the crest of the mountains in question. It is not uncommon in GOES imagery to be able to see what appears to be the rippling effects of mountain waves in the turbidity pattern associated with PEPEs.

Another commonly occurring phenomena within the boundary layer are parallel, counter-rotating roll vortices (LeMone, 1973), resulting from inflectional instability of the wind field which gives rise to phenomena such as cumulus cloud streets. These have been studied in great detail since the pioneering paper of Faller and Kaylor (1966). Subsidence may occur in long parallel bands perhaps 5 or 10 kilometers wide, interspersed between the upward motion zone capped by clouds. There are many other forms of convective instability in the heated boundary layer that are only partially understood. Over the oceanic areas these take on the more familiar patterns of Benard convection which have been graphically described by Agee (1984) using satellite imagery. Over land there is occasional evidence of the development of polygonal convection cells. Cumulus and small thunderstorms form in in the vertices of these open polygons which surround areas of large scale gentle, but persistent subsidence. These are rather transient and ephemeral features of the atmosphere, but may well become involved in the pseudo-CARE generating mechanism.

A more dramatic series of satellite photos shows pseudo-CARE. In Figure 38, a sequence of images beginning at 1437 and lasting through 2100 GMT, 30 August 1980, shows a widespread PEPE covering the southeastern United States from the mid-Ohio Valley southwards. What appears to be actual CAREs are seen during the early morning hours over eastern Alabama although they slowly become obscured by developing convective clouds as the day wears on. What is more interesting is the development of a progressively clearer slot that extends from Iowa through

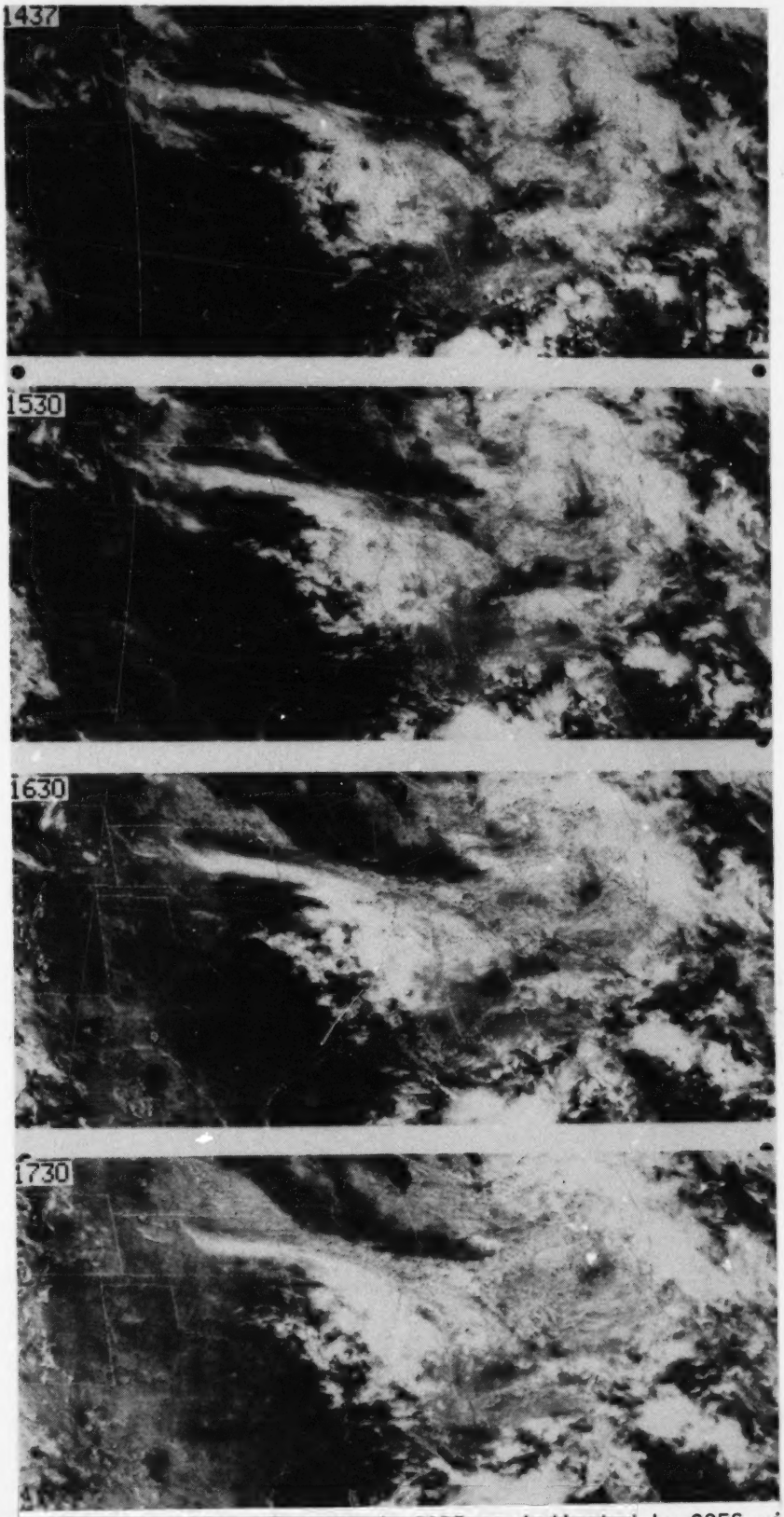

Figure 38. The generation of a pseudo-CARE as indicated by GOES visible imagery on 19 August 1980. Image sequences begin at 1437 GMT and continue through 2100 GMT. The last image is an infrared scene.

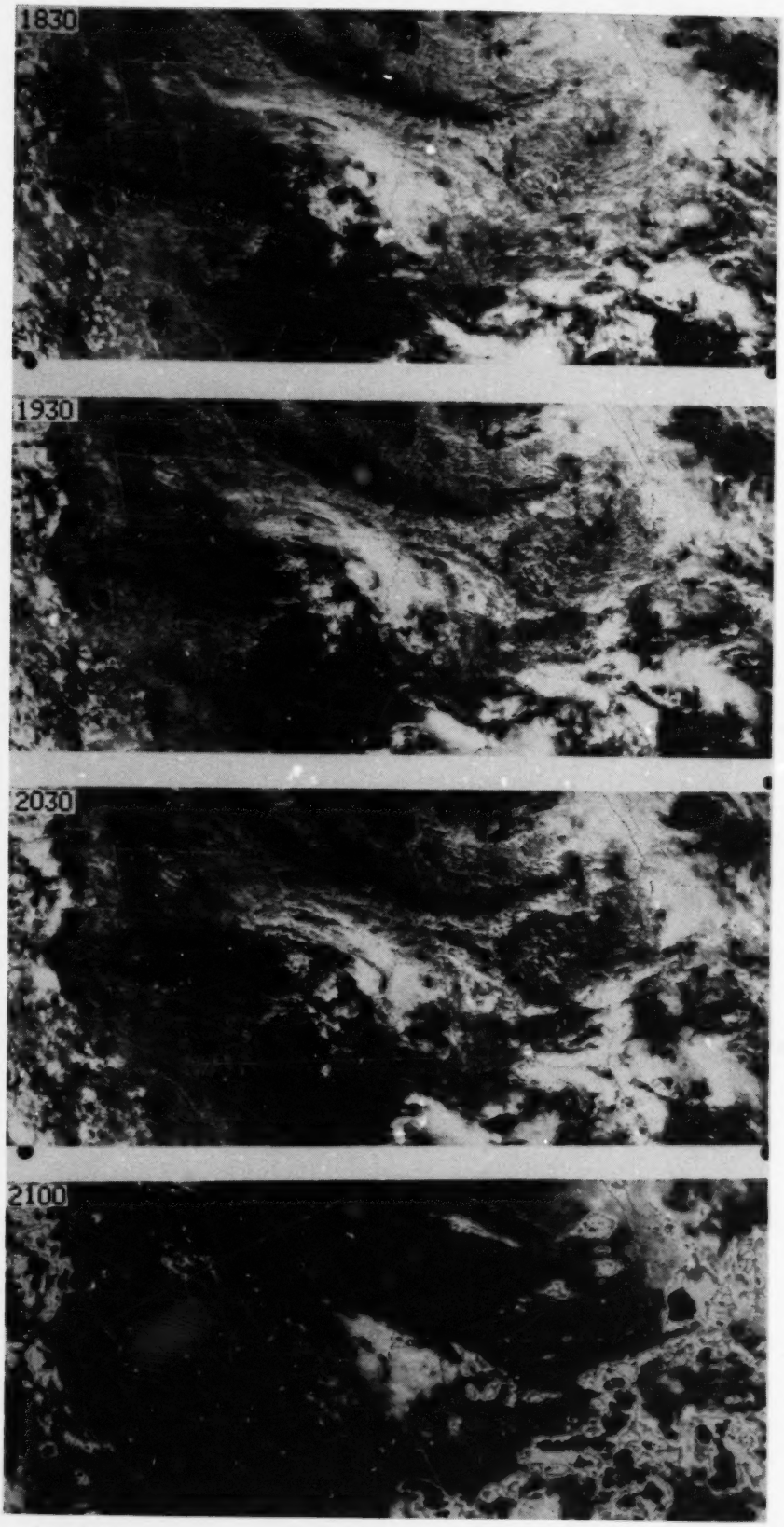

Figure 38 continued.

northeastern Missouri, central Illinois, southern Indiana, and along the Ohio River and ultimately goes into western Pennsylvania by the end of the day. Cumulus clouds are clearly suppressed while the ground contrast is enhanced, indicative of a lower optical depth of atmospheric aerosols. These features are clearly unrelated to any precipitation mechanism. Due to the propagation speeds involved, the clear slot could not be the result of advective phenomena. There has been considerable research over the past several years concerning mid-tropospheric circulation systems often associated with frontal boundaries and jet streams. A very similar, although somewhat smaller version of this type of clear slot was reported by Koch (1984). In his example what appeared to be a thermally direct frontogenetical circulation was related to the development of the major squall line. It also exhibited characteristics of greatly suppressed cumulus activity and therefore, by inference, strong subsidence in the lower troposphere. Careful inspection of Figure 38 shows what may be a second pseudo-CARE developed over northern Georgia and eastern Tennessee at 1830 GMT.

It has become apparent that there may, indeed, be a multitude of mechanisms resulting in inhomogeneities of PEPE aerosol hazes. This does not in any way invalidate the theory of precipitation-generated CAREs. However, it underlines the points made by Lyons and Calby (1983) that, as part of any organized program to monitor long-range transport and aerosol transformation, extensive supporting mesometeorological data must be gathered in order to properly interpret those aerosol measurements. Procedures which allow the gathering of mesoscale information in real-time in a convenient format for later analyses (satellite, radar, or lightning mapping) should be employed.

Furthermore, it should be standard operational procedure wherever possible during field programs to collocate all pollution and meteorological sensors so that a better understanding of interrelated phenomena may be gained.

Without an appreciation for the several apparent causes of polluted boundary layer inhomogeneities, it is possible that aerosol measurements made during transport and transformation experiments could be improperly interpreted. Lower aerosol concentrations might be considered as indicative of diminished transformation rates whereas an incident of entrainment of cleaner air from above may be the responsible agent.

EXTENDED BIBLIOGRAPHY

Agee, E.W., 1984: Observations from Space and Thermal Convection: A Historical Perspective. Bull. Amer. Meteor. Soc., 65, 938-949.

Altshuller, A.P., 1985: Relationships Involving Fine Particulate Mass, Fine Particle Sulfur and Ozone During Episodic Period at Sites in and around St. Louis, MO. Atmos. Environ., 19, 265-276.

Austin, P.M., and R.A. Houze, Jr., 1973: A Technique for Computing Vertical Transports by Precipitating Cumuli. J. Atmos. Sci., 30, 1100-1111.

Auvine, B., and C. E. Anderson, 1972: The Use of Cumulonimbus Anvil Growth Data for Inferences about the Circulation in Thunderstorms and Severe Local Storms. Tellus, 4, 300-311.

Behunek, J.L., T.H. VonderHaar, and P. Laybe, 1984: Determination of Cloud Parameters for NEROS II from Digital Satellite Data. Colorado State University, EPA-600/S3-84-004.

Braham, R.R. Jr., 1952: The Water and Energy Budgets of the Thunderstorm and their Relation to Thunderstorm Development. J. Meteor., 9, 227-242.

Bridgman, H.A., 1984: Mesoscale Spatial Variability of Sulfate in Air and Rainwater at St. Louis. Water, Air, Soil Pollut., 22, 153-160.

Browell, E.V., S.T. Shipley, C.F. Butler, and S. Ismail: 1983: Airborne Lidar Measurements of Aerosols, Mixed Layer Heights, and Ozone during the 1980 PEPE/NEROS Summer Field Experiment. NASA Langley Research Center, Langley, VA. To be Published.

Browning, K.A., 1964: Airflow and Precipitation Trajectories within Severe Local Storms which Travel to the Right of the Winds. J. Atmos. Sci., 21, 634-693.

Browning, KA., and F.H. Ludlam, 1962: Airflow in Convective Storms. Quart. J. Roy. Meteor. Soc., 88, 117-135.

Byers, H.R., and R.R. Braham, Jr., 1949: The Thunderstorm. U.S. Government Printing Office, Washington, D.C. 220 pp.

Calby, R.H., 1983: An Evaluation of GOES Visible Radiance Data for Monitoring Atmospheric Aerosol. MS Thesis, Dept. of Geophysical Sciences, University of Chicago. 75 pp.

Chatfield, R.B., and P.J. Crutzen, 1984: Sulfur Dioxide in Remote Oceanic Air: Cloud Transport of Reactive Precursors. J. Geophys. Res., 89, 7111-7132.

Ching, J., 1982: The Role of Convective Clouds in Venting Ozone from the Mixed Layer. Preprints, 3rd Joint Conf. on Applications of Air Pull. Meteor., AMS, San Antonio, TX.

Chorowski, LR., G.G. Campbell, J.M. Davis, and T. VonderHaar, 1981: Satellite Detection of A Forest Fire Plume near Eagle, Colorado. Dept. Atmos. Sciences, Colorado State University.

Clarke, J.F., and J.K.S. Ching, 1983: Aircraft Observations of Regional Transport of Ozone in the Northeastern United States. Atmos. Envir., 17, 1703-1712.

Coffey, P.E., and W.N. Stasiuk, 1975: Evidence of Atmospheric Transport of Ozone into Urban Areas. Environ. Sci. Techol., 9, 55-62.

Cotton, W.R., and R.A. Anthes, 1984: The Dynamics of Clouds and Mesoscale Meteorological Systems. Academic Press, Inc., New York (in press).

_____, 1983: Cloud Venting - Basic Concepts and Modeling Approaches. Specialty Conf. on Modeling Nonhomogeneous, Nonstationary, Urban Boundary Layers, AMS/EPA, Baltimore, MD.

Daum, P. H., S.E. Schwartz, and L. Newman, 1983: Acidic and Related Constituents in Liquid Water Stratform Clouds. J. Geophy. Res., 89, 1447-1458.

DeMarias, G.A., 1980: Air Pollution Concentrations Associated with Stagnation and Restricted Visibility. USEPA, ESRL, 72 pp.

Draxler, R.R. and A.D. Taylor, 1982: Horizontal Dispersion Parameters for Long-Range Transport Modeling. J. Appl. Meteorol., 21, 367-372.

Easter, R.C., 1984: The OSCAR Experiment, in, Deposition Both Wet and Dry. B.B. Hicks, Ed.,Vol. 4, Butterworth Publishers, Boston, MA, 97-120.

Emmanuel, K.A., 1979: Inertial Instability and Mesoscale Convective Systems: Part 1: Linear Theory of Inertial Instability in Rotating Viscous Fluids. J. Atmos. Sci., 36, 2425-2449.

Ernst, J.A., 1977: A NOAA-5 View of Alaskan Smoke Patterns. Bull. Amer. Meteor. Soc., 58, 1074-1076.

Faller, A.J., and R. Kaylor, 1966: A Numerical Study of the Instability of the Laminar Ekman Boundary Layer. J. Atmos. Sci., 23, 466-480.

Ferman, M.A., G.T. Wolff, and N.A. Kelly, 1982: The Nature and Sources of Haze in the Shenandoah Valley/Blue Ridge Mountains Areas. J. Air Poll. Cont. Assoc., 31, 1074-0182.

Fraser, R.S., Y.J. Kaufman, and R.L. Mahoney, 1984: Satellite Measurement of Aerosol Mass over Land. AMS Conf. on Satellite Remote Sensing Applications, Clearwater Beach, FL, 4-10.

Fritsch, J.M., and R.A. Maddox, 1981: Convectively Driven Mesoscale Weather Systems Aloft. Part I: Observation. J. Appl. Meteor., 20, 9-19.

Fujita, T.T., 1959: Precipitation and Cold Air Production in Mesoscale Thunderstorm Systems. J. Meteor., 16, 459-466.

_____, 1963: Analytical Mesometeorology: A Review. Meteorological Monographs #27, Amer. Meteor. Soc., Boston, MA.

Galloway, J.N., G.E. Likens, W.C. Keene, and J.M. Miller, 1982: The Composition of Precipitation in Remote Areas of the World. J. Geophy. Res., 87, 8771-8786.

Goff, R.C., 1976: Some Observations of Thunderstorm Induced Low-Level Wind Variations. AIAA 9th Fluid and Plasma Dynamics Conf., San Diego, CA, 7 pp.

Granat, L., 1978: Sulfate in Precipitation as Observed by the European Atmospheric Chemistry Network. Atmos. Enviro., 12, 413-424.

Greenhut, G.K., J.K.S. Ching, R. Pearson, and T.P. Repoff, 1984: Transport of Ozone by Turbulence and Clouds in an Urban Boundary Layer. J. Geophys. Res., 89, 4757-4766.

Haase, S.P., and R.K. Smith, 1984: Morning Glory Wave Clouds in Oklahoma: A Case Study. Mon. Wea. Rev., 112, 2078-2089.

Hane, C.E., 1973: The Squall Line Thunderstorm Numerical Experimentation. J. Atmos. Sci., 30, 1672-1690.

Hicks, B.B., and J.D. Shannon, 1979: A Method for Modeling the Deposition of Sulfur by Precipitation over Regional Scales. J. Appl. Meteor., 18, 1415-1418.

Hales, J.M., 1981: Atmospheric Chemistry and Source Receptor Relationships. In, METROMEX: A Review and Summary. S.A. Changnon, Ed., AMS Monographs, Boston, MA, 117-140.

_____, and M.T. Dana, 1979: Precipitation Scavenging of Urban Pollutants by Convective Storm Systems. J. Appl. Meteor., 18, 294-316.

Hegg, D.A., S.A. Rutledge, and P.V. Hobbs, 1984: A Numerical Model for Sulfur Chemistry in Warm-Frontal Rainbands. J. Geophys. Res., 89, 7133-7147.

Husar, R.G., D.E. Patterson, J.M. Holloway, W.E. Wilson, and T.G. Ellestad, 1979: Trends of Eastern U.S. Haziness since 1948. Fourth Symposium on Turbulence, Diffusion, and Air Pollution, AMS, Reno, NV.

Klemp, J.B., and R.B. Wilhelmson, 1978: The Simulation of Three-Dimensional Convective Storm Dynamics. J. Atmos. Sci., 35, 1070-1096.

Koch, S.E., 1984: The Role of an Apparent Mesoscale Frontogenetical Circulation in Squall Line Initiation. Mon. Wea. Rev., 112, 2090-2111.

Lamb, R.G., 1981: A Regional Scale (1000 km) Model of Photochemical Air Pollution. Part I: Theoretical Formulation. U.S. EPA, Meteor. and Assess. Div., Research Triangle Park, NC, 22 pp.

Leaderer, B.P., and J.A. Stolwijk, 1980: Optical Properties of the Urban Aerosol and their Relation to Chemical Composition. Annals of the New York Academy of Science, 338, 70-85.

_____, and R.L. Tanner, P.J. Lioy, and J.A. Stolwijk, 1981: Seasonal Variations in Light Scattering in the New York Region and their Relation to Sources. Atmos. Envir., 15, 2407-2420.

LeMone, M.A., 1973: The Structure and Dynamics of the Horizontal Roll Vortices in the Planetary Boundary Layer. J. Atmos. Sci., 30, 1077-1091.

Liu, M.K., and D.A. Stewart, 1982: A Mathematical Model of the Analysis of Acid Deposition. J. Appl. Meteor., 21, 859-873.

Lyons, W.A., R.H. Calby, and C.S. Keen, 1985: The Impace of Mesoscale Convective Systems on Regional Visibility and Oxidant Distrubtion During Persistent Elevated Pollution Episodes, J. Clim. and Appl. Meteor., (in press).

_____, and R.H. Calby, 1983: Impact of Mesoscale Convective Precipitation Systems on Regional Visability and Ozone Distributions. Final Report, EPA Contract 68-02-3740, EPA/ESRL, Research Triangle Park, NC, 96 pp.

_____, C.S. Keen, and J.A. Schuh, 1983: Modeling Mesoscale Diffusion and Transport Processes for Releases within Coastal Zones during Land/Sea Breezes. USNRC, NUREG/CR-3542, 184 pp.

_____, and R.H. Calby, 1982a: Air Quality Applications of Meteorological Satellite Data. Paper No. 82-633, 75th Annual Meeting of the Air Poll.Cont. Assoc., New Orleans, LA, 16 pp.

_____, _____, 1982b: Meteorological Conditions and Episode Morphology for PEPE/NEROS 1980. EPA-45-DRAFT, U.S. Environmental Protection Agency, Research Triangle Park, NC. 66 pp.

_____, R.H. Calby, S.J. Fage, and M.A. Lazaro, 1981: Planetary Boundary Layer Structure during PEPE/NEROS 1980 using Doppler Acoustic Sounding. Paper No. 81-62.4, 74th Annual Meeting of the Air Pollution Control Assoc., Philadelphia, PA.

_____, 1980: Evidence of Transport of Hazy Air Masses from Satellite Imagery. Annals of New York Academy of Sciences, 338, 418-433.

_____, J.C. Dooley, Jr., and K.T. Whitby, 1978: Satellite Detection of Long Range Pollution Transport and Sulfate Aerosol Hazes. Atmos. Envir., 12, 612-631.

_____, E.M. Ruben, 1976: Aircraft measurements of the Chicago Urban Plume at 100 km Downwind. Preprints, Third Symp. Atmos. Turb., Diffusion and Air Quality, AMS, Raliegh, NC, 8 pp.

_____, and H.S. Cole, 1976: Photochemical Oxindant Transport: Mesoscale Lake Breeze and Synoptic Scale Aspects. J. Appl Meteor., 15, 733-743.

_____, and R.B. Husar, 1976: SMS/GOES Visible Images Detect Synoptic Scale Air Pollution Episode. Mon. Wea. Rev., 104, 1623-1626.

_____, 1975: Satellite Detection of Air Pollutants, in, Remote Sensing Energy - Related Studies. T. Veziroglu, Ed., John Wiley, NY, 263-270.

_____, C.S. Keen, and R.A. Northouse, 1974: ERTS-1 Satellite Observations of Mesoscale Air Pollution Dispersion around the Great Lakes. Preprints,

Symposium on Atmospheric Diffusion and Air Pollution, AMS, Santa Barbara, CA, 273-280.

_____, and S.R. Pease, 1973: Detection of Particulate Air Pollution Plumes from Major Point Sources using ERTS-1 Imagery. Bull. Amer. Meteor. Soc., 54, 1163-1170.

_____, and L.E. Olsson, 1973: Detailed Mesometeorological Studies of Air Pollution Dispersion in the Chicago Lake Breeze. Mon. Wea Rev., 101, 387-403.

_____, 1971: Low Level Divergence and Subsidence Over the Great Lakes in Summer. Proc., 14th Conf. on Great Lakes Res., IAGLR, 467-487.

_____, 1970: Mesoscale Regimes over the Southern Basin of Lake Michigan and Their Effect Upon Summertime Convective Clouds. Ph.D. Dissertation, Dept.

Mack, R.A., and D.P. Wylie, 1982: An Estimation of the Condensation Rates in Three Severe Storm Systems from Satellite Observations of the Convective Mass Flux. Mon. Wea. Rev., 110, 725-744.

Maddox, R.A., 1980: Mesoscale Convective Complexes. Bull. Amer. Meteor. Soc., 61, 1374-1387.

MAP3S/RAINE, 1981: Biennial Progress Report for the Period FY 1980-81. Report PNL-4096, Pacific Northwest Laboratory, Richland, WA.

McNider, R., and R.A. Pielke, 1979: Application of the University of Virginia Mesoscale Model to Air Pollution Transport. Preprints, Fourth Symposium on Turbulence, Diffusion and Air Pollution. AMS, Reno, NV, 397-404.

McPherson, M.B., 1981: Integrated Control of Combined Sewer Regulators Using Weather Radar. EPA-600/2-81-041, U.S. EPA, Cincinnati, OH, 84 pp.

Millan, M.M., and Y.S. Chung, 1977: Detection of a Plume 400 km from the Source. Atmos. Environ., 11, 933-944.

Mohr, T., 1971: Picture of the Month: Air Pollution Photographed by Satellite. Mon. Wea. Rev., 99, 653.

NCAR, 1984: The NCAR Acid Deposition Modeling Project, Regional Acid Deposition: Models and Physical Processes, EPA Report EPA-600/3-84-0541, Research Triangle Park, NC.

Newton, C.W., 1966: Circulations in Large Sheared Cumulonimbus. Tellus, 4, 699-712.

Niemann, B.L., 1982: An Analysis of Regional Acid Deposition Episodes and the Feasibility of their Deterministic Simulation. U.S. Environmental Protection Agency, Acid Rain Staff Report, Washington, D.C.

_____, 1980: Sulfate, Visibility, and Precipitation Chemistry Data Bases and Results for Regional Modeling, Invited Paper, EPA, Regional Air Pollution Modeling Workship, Port Deposit, MD.

_____, A.H. Hirata, B.R. Hall, M.T. Mills, P.M. Mayerhoffer, and L.F. Smith, 1980: Initial Evaluation of Regional Transport and Subregional Dispersion Models for Sulfur Dioxide and Fine Particulates. Joint Conf. on Applications of Air Pollution Meteor., AMS, New Orleans, LA, 216-224.

Nitta, J., 1975: Observational Determination of Cloud Mass Flux Distributions. J. Atmos. Sci., 32, 73-91.

Norton, C.C., F.R. Mosher, B. Hinton, D.W. Martin, D. Santek, and W. Kuhlow, 1980: A Model for Calculating Desert Aerosol Turbidity over the Oceans from Geostationary Satellite Data. J. Appl Meteor., 19, 633-644.

Orndorff, B.L., 1982: A Case Study of the Distribution and Transport of Intense Haze over the Southeastern United States. Master's Thesis. Old Dominion University, Norfolk, VA.

Ott, S., and W.A. Lyons, 1977: Further Evidence of Long-Range Photochemical Oxidant Transport Inferred from Acoustic Sounder Data. In Proceedings, AMS/APCA Joint Conference on Applications of Air Pollution Meteorology, 33-38.

Parmenter, F.C., 1978: Delineating Haze and Pollution Boundaries from Satellite Data. NOAA, Satellite Applications Information Note 77/15, 5 pp.

Patrinos, A.A.N., 1985: The Impact of Urban and Industrial Emissions on Mesoscale Precipitation Quality. J. Air. Poll. Control Assoc., 35, 719-727.

Patterson, D.E., R.B. Husar, and C. Hakkarinen, 1979: Monte Carlo Simulation of Daily Sulfate Distribution in the Eastern U.S.: Comparison with SURE Data and Visibility Observations. Symposium, Potential Environmental and Health Consequences of Atmospheric Sulfur Deposition, ORNL, Gatlinburg, TN. 20 pp.

Pecnick, M.J., and J.A. Young, 1984: Mechanics of a Strong Subsynoptic Gravity Waves Deduced from Satellite and Surface Observations. J. Atmos. Sci., 41, 1850-1862.

Possiel, N.C., J.F. Clarke, T.L. Clark, J.K. Ching, and E.L. Martinez, 1982: Recent EPA Urban and Regional Scale Oxidant Field Programs in the Northeastern U.S. Paper No. 82-24.1, 75th Annual Meeting of the Air Poll. Cont. Assoc., New Orleans, LA.

Purdom, J.F.W. and K. Marcus, 1982: Thunderstorm Trigger Mechanisms over the Southeast United States. Preprints, 12th Conf. on Severe Local Storms, AMS, San Antonio, Tx. 487-488.

_____, 1976: Some Uses of High-Resolution GOES Imagery in the Mesoscale Forecasting of Convection and its Behavior. Mon. Wea. Rev., 111, 602-607.

_____, 1973: Meso-highs and Satellite Imagery. Mon. Wea. Rev., 101, 180-181.

Raynor, G.S., and J.V. Hayes, 1981: Acidity and Conductivity of Precipitation on Central Long Island, New York in Relation to Meteorological Variables. Water, Air, and Soil Poll., 15, 229-245.

Robock, A., and M. Matson, 1983: Circumglobal Transport of the El Chicon Volcanic Dust Cloud. Science, 221, 195-197.

Ruff, R.E., R.L. Mancuso, and W.B. Johnson, 1981: Long-Range Transport Modeling of Atmospheric Sulfur Effluents from the Natuna LNG Project, Vols. I, II, Final Report, SRI International.

Samson, P.J. and K.W. Ragland, 1977: Ozone and Visibility Reduction in the Midwest: Evidence of Large-Scale Transport. J. Appl. Meteor., 16, 1101-1106.

Schlesinger, R.E., 1978: A Three-Dimensional Numerical Model of an Isolated Thunderstorm: Part I, Comparative Experiments for Variable Ambient Wind Shear. J. Atmos. Sci., 35, 690-713.

Scott, B.C., 1982: Predictions of In-Cloud Conversion Rates of SO_2 and SO_x Based upon a Single Chemical and Kinetic Storm Model, Atmos. Environ., 16, 1735-1752.

_____, 1978: Parameterization of Sulfate Removal by Precipitation. J. Appl. Meteor., 17, 1375-1388.

Semonin, R.G., 1977: Temporal and Spatial Variability of Rainfall pH. Proceedings Conf. on Metropolitan Physicl Environment, 53-61.

_____, 1982: Precipitation, Chemical Depositions, and Water Resource Issues. 55th Conf. Water Pollution Control Federation, St. Louis, MO, 16pp.

Shannon, J.D., 1979: The Advanced Statistical Trajectory Regional Air Pollution Model. Preprints, Fourth Symposium Turbulence, Diffusion, and Air Pollution, AMS, Reno, NV, 376-380.

Shenk, W.E. and R.J. Curran, 1974: The Detection of Dust Storms Over Land and Water with Visible and Infrared Measurements. Mon. Wea. Rev., 102, 830-836.

Shipley, S.T., E.V. Browell, B.L. Orndorff, and D.S. McDougal, 1983: Airborne Lidar Observations of Long-Range Transport in the Free Troposphere. Preprints 6th Symposium on Turbulence and Diffusion, Boston, MA, Amer. Meteor. Soc.

Sikdar, D.N., V.E. Suomi, and C.E. Anderson, 1970: Convective Transport of Mass and Energy in Severe Storms over the USA: An Estimate from Geostationary Altitude. Tellus, 22, 521-532.

Suchman, D., D.W. Martin, and D.S. Sikdar, 1977: Deep Convective Mass Transports: An Estimation from Geostationary Satellites. Mon. Wea. Rev., 105, 943-955.

Tanner, R.L., R, Kumar, and S. Johnson, 1984: Vertical Distribution of Aerosol Strong Acid and Sulfate in the Atmosphere. J. Geophys. Res., 89, 7149-7158.

Trijonis, J.., 1978: Visibility in the Southwest - An Exploration of the Historical Data Base. EPA 600/3-78-039, USEPA, RTP, NC.

Tripoli, G.J., and W.R. Cotton, 1982: The Colorado State University Three-Dimensional Cloud/Mesoscale Model - 1982: Part 1: General Theoretical Framework and Sensitivity Experiments. J. Res. Atmos., 16, 188-219.

UCAR, 1983: The National STORM Program. University Corporation for Atmospheric Research, Boulder, CO, 34 pp.

Vaughan, W., M. Chan, B. Cantrell and F. Pooler, 1982: A Study of Persistent Elevated Pollution Episodes in the Northeastern United States. Bull. Amer. Meteor. Soc., 63, 258-266.

Waldman, J., J.W. Munger, D.J. Jacob, R.C. Flagan, J.J. Morgan, and M.R. Hoffman, 1982: Chemical Composition of Acid Fog. Science, 218, 677-679.

Wakimoto, R.M., 1982: The Life Cycle of Thunderstorm Gust Fronts as Viewed With Doppler Radar and Radiosonde Data. Mon. Wea. Rev., 110, 1060-1082.

Wash, C.H., and T.M. Whittaker, 1980: Subsynoptic Analysis and Forecasting with an Interactive Computer System. Bull. Amer. Meteor. Soc., 61, 1591.

Watson, G.F. and W.J. Saucier, 1979: Statistics of Elevated Pollution Episodes. Final Report to the Research Triangle Institute, Subcontract #1-43U-1714. Research Triangle Park, NC, 28 pp.

White, W.H., J.A. Anderson, D.L. Blumenthal, R.B. Husar, N.V. Gillani, J.D. Husar, and W.E. Wilson, 1976: Formation and Transport of Secondary Air Pollutants: Ozone and Aerosols in the St. Louis Urban Plume. Science, 194, 187-188.

Wisniewski, J., and J.D. Kinsman, 1982: An Overview of Acid Rain Monitoring in North America. Bull. Amer. Meteor. Soc., 63, 598-627.